Laboratory Evaluation of Bond Between Bituminous Paving Layers

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Certificate

This is to certify that the work in the thesis entitled "**Laboratory Evaluation of Bond between Bituminous Paving Layers**" by **Jyoti Prakash Giri** is a record of an original work carried out by him under my supervision and guidance in partial fulfillment of the requirements for the award of the degree of **Master of Technology** in **Department of Civil Engineering** with specialization in **Transportation Engineering.** Neither this project nor any part of it has been submitted for any degree or academic award elsewhere.

Prof. Mahabir Panda
Professor
Department of Civil Engineering
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Dedicated to my

(Late) Grandfather and (Late) Grandmother

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Abstract

A bituminous pavement is a multi-layered structure generally made up of surfacing, base and sub base courses on a sub grade. An interface is said to be a boundary between any two consecutive layers. So an adequate bond between the layers at the interfaces must be ensured so that multiple layers perform as a single composite structure. In case of non-bituminous layers or bituminous-non bituminous layers, adequate bond is established as such due to the mechanical interlocking between the aggregate surfaces. However, the state of bond at the interface between any two bituminous layers has a significant influence on the stress distribution across pavement layers under traffic loads and hence on the overall performance of the pavement. To increase the adhesion or bonding between two bituminous layers, bituminous tack coats are applied prior to overlay. This study is an attempt to evaluate the interface bond strength between two types of bituminous layer combinations in the laboratory. The cylindrical specimens have been tested for bond strength at four normal service temperatures, namely 25^0, 30^0, 35^0 and 40^0C by applying different types of tack coat at varying application rates. The specimens have been prepared using normal Marshall Procedure first for the underlying layer, followed by application of tack coat and finally overlaying with the top layer in the same mould in an appropriate manner. Two types of layer combinations have been tried, namely (i) Bituminous Concrete (BC) layer on Dense Bituminous Macadam (DBM) samples and (ii) Semi Dense Bituminous Concrete (SDBC) layer on Bituminous Macadam (BM) samples. Similarly, different types of tack coat materials namely bitumen, Cationic Rapid Setting with low viscosity (CRS-1) and Cationic Medium Setting with high viscosity (CMS-2) emulsions have been used for the interface bond between the said bituminous layers. The samples thus prepared have then been tested on a specially fabricated attachment (named bond strength device) fixed to the loading frame of the

Modified Marshall Testing Apparatus. It is observed that the interlayer bond strength depends on the test temperature and this decreases with increase in test temperature. It is also observed that the bond strength depends on the type of tack coat used and conditions of the type of combinations. The optimum amount of tack coat has been found to vary for tack coat type and layer combination type.

Key words*:* *Interlayer Bond strength, Tack coat, Bituminous layer combination, Bond strength device.*

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Abbreviations

RS	-	Rapid Setting
MS	-	Medium Setting
SS	-	Slow Setting
RC	-	Rapid Curing
MC	-	Medium Curing
CRS	-	Cationic Rapid Setting
CMS	-	Cationic Medium Setting
CSS	-	Cationic Slow Setting
HMA	-	Hot Mix Asphalt
ILBS	-	Interlayer Bond Strength
DBM	-	Dense Bituminous Macadam
BC	-	Bituminous Concrete
BM	-	Bituminous Macadam
SDBC	-	Semi Dense Bituminous Concrete
MORT&H	-	Ministry Of Road Transport and Highways
IS	-	Indian Standard
ASTM	-	American Society for Testing and Materials
M	-	Meter
mm	-	Millimeter
kN	-	Kilo newton
cm	-	Centimeter

in	-	Inch
MTS	-	Material Testing System
psi	-	Pound-force per square inch
AC	-	Asphalt Cement
PG	-	Performance Graded
PCC	-	Portland Cement Concrete
gal	-	Gallon
yd	-	Yard
Kg	-	Kilogram
g	-	Gram
Sec	-	Second
kPa	-	Kilopascal
R	-	Radius

Chapter I

Introduction

General

Failures arise due to inadequate bond

Background of Tack coat

Objectives

Organizations of Thesis

1.1 General

Highways are considered to be the backbone of a country's growth and development. All developed as well as developing countries normally have a continuous program of sustaining and building road infrastructures or developing the existing road. To improve the existing road infrastructure in view of increased traffic is to strengthen the existing pavement layer by overlaying with another layer of appropriate material composition and thickness. The flexible pavement is generally designed and constructed in several layers for effective stress distribution across the pavement layers under the varying heavy traffic loads. The viscous nature of the flexible pavement, allows its different layers to sustain significant plastic deformation, although distresses due to repeated heavy loading over time which is the most common failure mechanism. The flexible pavement works as a single structure due to good bonding between the different layers interface of it. It is generally believed that, the pavement stress distribution is extremely influenced by the adhesion conditions at the layer interface. Poor adhesion at layer interface may cause adverse effects on the structural strength of the pavement system and form numbers of premature failures. To increase bonding between layers, bituminous tack coats are applied prior to overlay. Bituminous emulsions are normally used as tack coats. In spite of their extensive application, the thoughts among pavement engineers differ regarding the effectiveness of tack coat in enhancing the adhesion between the two layers. This tack coat also made of a thin layer of bitumen residue and its objective is to provide adequate adherence between the layers. If the quantity of bituminous emulsions used is in excess or less than the required one, the interface bonding will not be satisfactory.

1.2 Failures arise due to inadequate bond

A Number of premature pavement failures can be attributed due to loss of bond between two layers of hot mix asphalt (HMA). It has been generally observed that poor adhesion between pavement layers contributes to major pavement overlay distresses and numbers of premature failures. Such are Slippage failure and Surface layer Delamination.

Slippage failure grows when the pavement layers begin to slide on one another and generally the top layer separating from the lower layer. This type of failure develops due to lack of bond between two top important pavement layers and it’s mainly seen at high horizontal force at points where traffic is accelerating or decelerating, such as at traffic signals and within horizontal curves.

Figure 1.1 Slippage failure [www.pavementinteractive.org]

Delamination is a section of a surface layer that has come loose from the pavement. The causes of this type of failure are slippage between layers and poor interlayer bond between the pavement layers. Other pavement problems that have been linked to poorer bond strength between pavement layers shape of a crescent are shown in figure.

Figure 1.2 Surface layer Delamination [www.roadscience.net]

1.3 Background of Tack coat

The word tack relates to a sort of stickiness. The coat is a small thickness of layer. So tack coat is a light application of a bituminous emulsion between pavement layers, most probably applied in a thin layer between an existing and a newly constructed bituminous surface. The importance of glue or sticky material like tack coat is to provide appropriate adhesive interlock between paving layers so that they react as a monolithic structure. Emulsified bitumen is a mixture of bituminous binder, water and emulsifying agent. The emulsifying agent might be soap, dust or colloidal clays. The structural view as reported by Roberts et al. (1996) is shown in figure1.3. Bituminous particles are kept in suspension in the water by the emulsifying agent and thus bitumen consistency is reduced at ambient temperature from a semi-solid to an applicable liquid form. So this liquefied bitumen is easier to distribute over a surface at ambient temperatures. When this liquid bitumen is applied to a clean bitumen surface, the water evaporates from the emulsion and leaving behind a thin layer of residual bituminous on the pavement surface.

Usually, hot bituminous binder, cutback bitumen or bituminous emulsions are used as tack coat materials for construction purpose. The use of bituminous emulsions as a tack coat material is escalating instead of cutback asphalt or hot bituminous binder. It can be applied at lower application temperatures compared to cutback bitumen or hot bituminous binder so it is easy to handle in field condition. Emulsified bitumen do not contain any harmful volatile chemicals comparatively pollution free and an environmentally friendly.

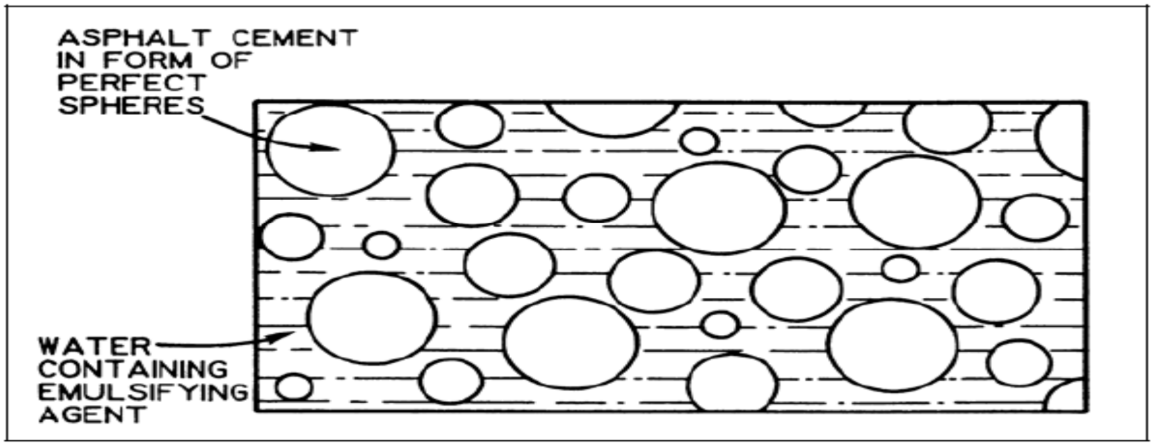


Figure 1.3 Composition of Bituminous Emulsion [Roberts et. al. 1996]

The type of emulsifying agent used in the bituminous emulsion would determine whether the emulsion anionic, or cationic. Cationic emulsions have bituminous droplets which carry a positive charge and anionic having negatively charged bituminous droplets. Also emulsified bitumen is graded as per their setting rate, which indicates how quickly the water evaporates from the emulsion such are rapid setting (RS), medium setting (MS), and slow setting (SS). The main difference between anionic and cationic emulsions is that the cationic emulsion evaporates water faster than the anionic emulsion. The anionic grades are RS-1, RS-2, MS-1, MS-2, MS-2h, SS-1 and SS-1h. The cationic grades named as CRS-1, CRS-2, CMS-2, CMS-2h, CSS-1, and CSS-1h. The absence of letter “C” in an emulsion denotes an anionic one and vice-versa. The letter “h” stands for hard grade bitumen binder (low penetration) and the numbers “1” and “2” indicates low and high viscosity respectively (Patel, 2010).

Cutback bitumen is also liquid bitumen produced by adding petroleum solvents like gasoline and kerosene to bituminous binder. The use of cutback bitumen as a tack coat material has declined rapidly over the years due to environmental anxieties and the health risk due to gas evaporate into the atmosphere from solvents. It is divided into two groupings, Rapid Curing (RC) and Medium Curing (MC) based on the type of solvent used. Rapid curing cutback uses solvent gasoline while medium curing cutback uses kerosene. Hot bituminous binders are obtained from the distillation of crude oil also used as tack coat. Unlike emulsions, bituminous binder particles do not carry any charge. Any grade of bituminous binder is acceptable as a tack coat material, even if it is generally preferable to use the same grade of bituminous binder used in the HMA for tack coat (CPB 03-1, Tack Coat Guidelines, 2003).

1.4 Objectives

Based on the discussions as mentioned above, the objectives of the present study have been identified as follows

- ✓ Fabrication of a simple testing arrangement to be used in a conventional Modified Marshall test apparatus to determine directly the interlayer bond strength between two layers.
- ✓ Experimentation using the fabricated device in respect of various material combinations.
- ✓ Preparation of samples under varying conditions, such are temperature, percentage of emulsions, with no tack coat use, by using bitumen as tack coat and setting time.

1.5 Organizations of the Thesis

The thesis has been presented as per following chapters.

(i) Chapter-I, general information about the interface bond strength between bituminous paving layers and objectives of the present studies is described.

(ii) Chapter-II, a brief review of the recent past studies carried out in laboratories to evaluation of the bond strength.

(iii) Chapter-III, described the experimental methodology carried out in this study for observing the interlayer bond strength between bituminous paving layers.

(iv) Chapter-IV, analyzed the results and discussion about the experimental investigations.

(v) Finally in Chapter-V a summary of the present study and the major conclusions are explained here with recommendation for future work.

Chapter II

Review of Literature

2.1 Introduction

This chapter focused on an extensive literature review on some field and laboratory studies that were conducted in the recent past to observe the pavement interlayer bond strength. It also elaborates on the various factors that affect pavement interlayer bond strength.

2.2 Past Studies on Evaluation of Pavement Interlayer Bond Strength

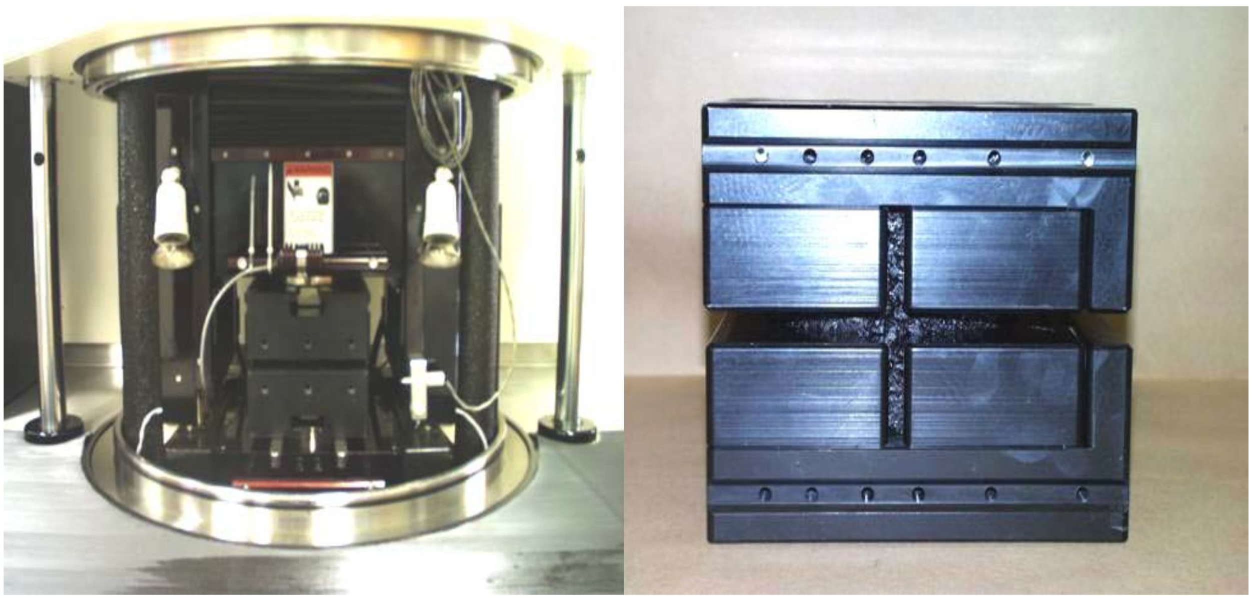
Bituminous pavements are generally constructed in several layers and proper bonding between adjacent layers is required to ensure good performance. But, this is not always achieved and a number of premature pavement failures have been developed due to poor bonding condition. The interface bond failure paving layers is due to mainly shear force only. In the recent past, interlayer shear performance has been broadly investigated. These studies have typically developed a unique test method or instrument for analysis of the interface bond strength. Various organizations and numbers of researchers have used various test methods for observing the pavement interlayer bond strength performance.

Uzan et al. (1978) used a direct shear test device to test with a 60-70 penetration asphalt binder as a tack coat at five different application rates. The tests were conducted in two different temperature 77 and 131^0F (25 and 55^0C). The tack coat was applied on the bottom layer and 3cm (1.8inch) of mix compacted on top. The direct shear device was developed considering the specimen size with a constant displacement rate of 2.5 mm/min (0.098 in/min). The shear strength was evaluated at five different normal loading pressures of 0.05, 0.5, 1.0, 2.5 and 5 Kg/cm^2. The shear strength increased when the test temperature decreases and the normal pressure increases. The observed optimum tack coat application rate for this studied was 1.0 Kg/m^2 at 25^{0}C.

In Delft University of Technology Molenaar et al. (1986) used a shear test device to determine the shear resistance of the tack coat at the interface of the asphalt layers. The device was mounted on a standard Marshall Stability loading press for applied a load at a rate of 0.85 mm/Sec. This device held bottom part of the compacted cylindrical specimens and shear load was applied perpendicular to the axis of the specimens of the top layer.

In Canada, Mrawira and Damude (1999) observed the bond strength of the interface by direct shear test. The specimens were collected as field cores from in-service pavements. Cores were assembled in six subsets varying with pavement age. All specimens were the same type of mix and the same type of materials used. The cores were trimmed to a height of 8cm (3.15 inch) and at the top surface of the layer 0.2 to 0.3 L/m^2 of SS1 emulsion was applied with set times left less than one hour. When the tack coat cured, 16mm nominal maximum aggregate size compacted on the core in two lifts with 75 Marshall blows per lift as a overlays. The specimen were left to cure for two weeks at room temperature, then cut into rectangular size and placed in a water bath at 22^{0}C (75^{0}F) for thirty minutes. The specimens were sheared on a guillotine style machine at a constant displacement rate of 1 mm/min.

Mohammad et al. (2002) evaluated the bond strength of tack coat used in the interface of the bituminous paving layers by using the Superpave shear tester shown in figure 2.2, which consists of a shear box set up for 150 mm (6 inch) diameter specimens. The specimens were compacted up to 50 mm and tack coat applied in five different application rates (0.0 to 0.9 L/m^2), the samples were allowed to cure and second lift is placed on top and compacted. The tack coat bond strength evaluated with two PG asphalt binders (PG 64-2P and PG 76-22M) and four emulsified asphalts (CRS-2P, CSS-1, SS-1 and SS-1h). The test was conducted on two test temperatures 25 and 55^{0}C (77 and 131^{0}F). They observed CRS-2P emulsion as the best performer and 25^{0}C (77^{0}F) test temperature gives five times more shear strength then 55^{0}C (131^{0}C).



(a) Shear box in SST (b) Shear Box with Prepared Sample

Figure 2.1 Superpave Shear Tester (Mohammad et al. 2002)

The Leuter shear strength test device was modified by Sangiorgi et al. (2002) in Germany for evaluating the interlayer bond strength based on a simple means of undertaking the direct shear test. The device was mounted on Marshall and CBR loading press. The specimens were used for test having 150 mm diameter, may be field cores or laboratories fabricated. The load was transferred to the specimen at a constant displacement rate of 50 mm/min with maintaining a temperature of 20^{0}C. A gap of 4.8mm provided between the shearing planes to minimize the friction. This testing device is standard in Austria, has also been adopted in the UK. Three different interfaces treatments were considered to simulate actual conditions: (i) with tack coat emulsion, (ii) contaminated by dirt and without tack coat emulsion, and (iii) with tack coat emulsion and a thin film of dirt. The results observed that the best interface bond strength was attained with an interface treatment prepared using an emulsified tack coat, while the poorest bond conditions were observed on a dirty surface without emulsion.

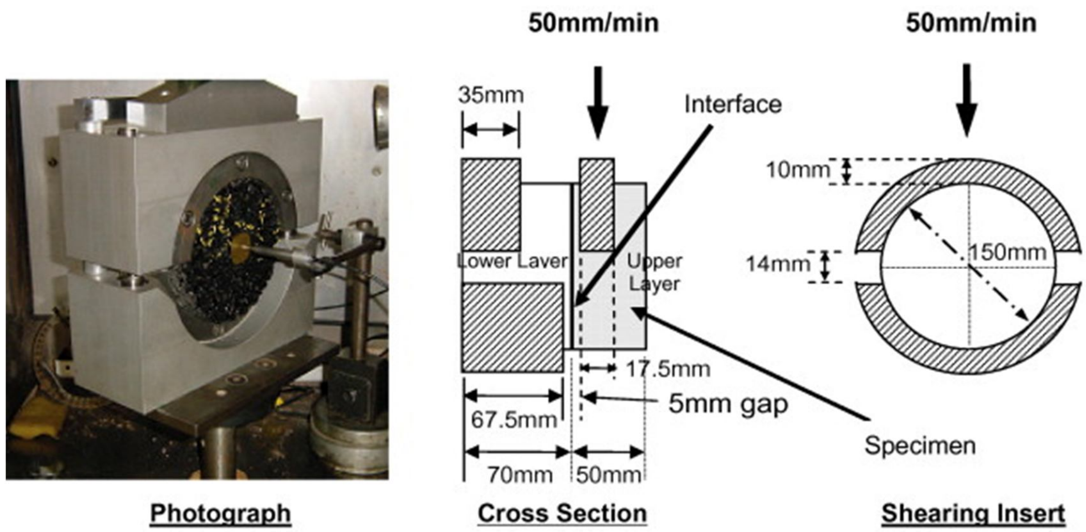


Figure 2.2 Leutner Shear Strength Tester (Sangiorgi et al., 2002)

Sholar et al. (2002) was developed a simple direct shear test device to measure the shear strength of field cores at their interface. The test was performed at 25^{o}C (77oF), with a constant rate of loading 50.8 mm/min (2in/min). The field cores were obtained from test sections with no tack, and with 0.091, 0.266 and 0.362 l/m^2 (0.02, 0.06, 0.08gal/yd2) tack coat application rate.

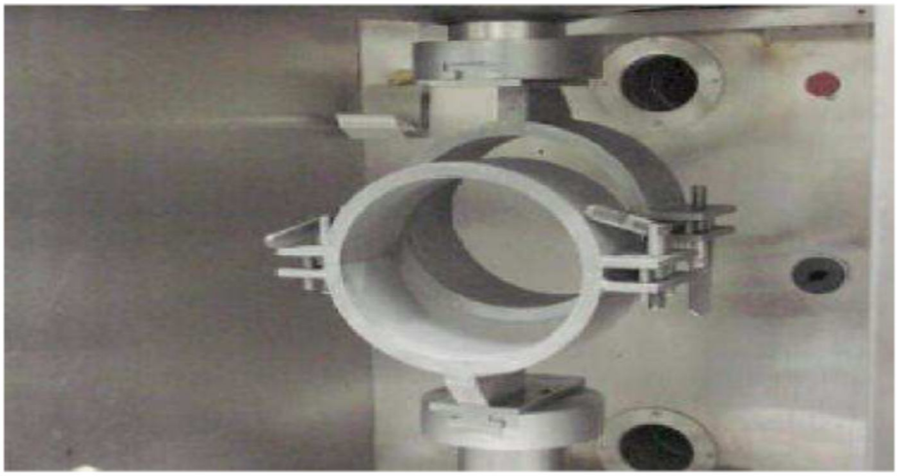


Figure 2.3 Simple Shear Test Device (Sholar et al., 2002)

The Layer-Parallel Direct Shear test device was an EMPA (Swiss Federal Laboratories for Materials Testing and Research) modified version of the device developed by Leutner (1979) in Germany. Raab and Partl (2004) were modified it and one part of the 150 mm diameter cylindrical specimen placed on a circular u-bearing and held with a well-defined clamp. The other part was suspended to allow for transferring the shear force, induced by a semicircular shear yoke with a constant deformation rate of 50.8 mm/min. This modified device was easily fitted to an ordinary servo-hydraulic Marshall testing machine or any standard universal testing machine. The tests were conducted at a temperature of 20^0C by keeping the specimens in a climate chamber for 8 hours. The shear strength of the interface was evaluated by using the following equation.

$$\tau = \frac{F}{A} = \frac{4F_{max}}{d^2\pi} \qquad (2.1)$$

Where τ= Maximum shear strength

A = Cross sectional area of specimen.

d = Diameter of the specimen

F_{max}= Maximum load

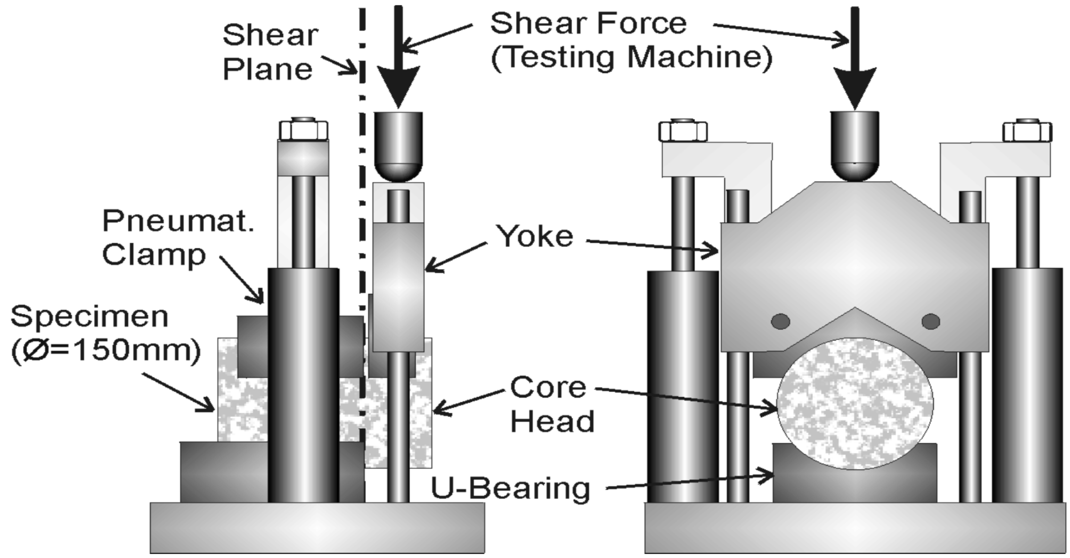


Figure 2.4 Schematic view of the LPDS (Layer-Parallel Direct Shear) test device with pneumatic clamping (Raab and Partl, 2004)

Swiss Federal Laboratories for Materials Testing and Research was developed a testing device for evaluating the bond strength of the HMA layers interface called Swiss LPDS Tester. The tests on this device was conducted on 150mm (6 inch) diameter field cores or laboratories fabricated samples with a constant loading rate of 50.8 mm/min (2 in/min). The minimum shear force required 15 kN for the bond between thin surface layers and the binder course.

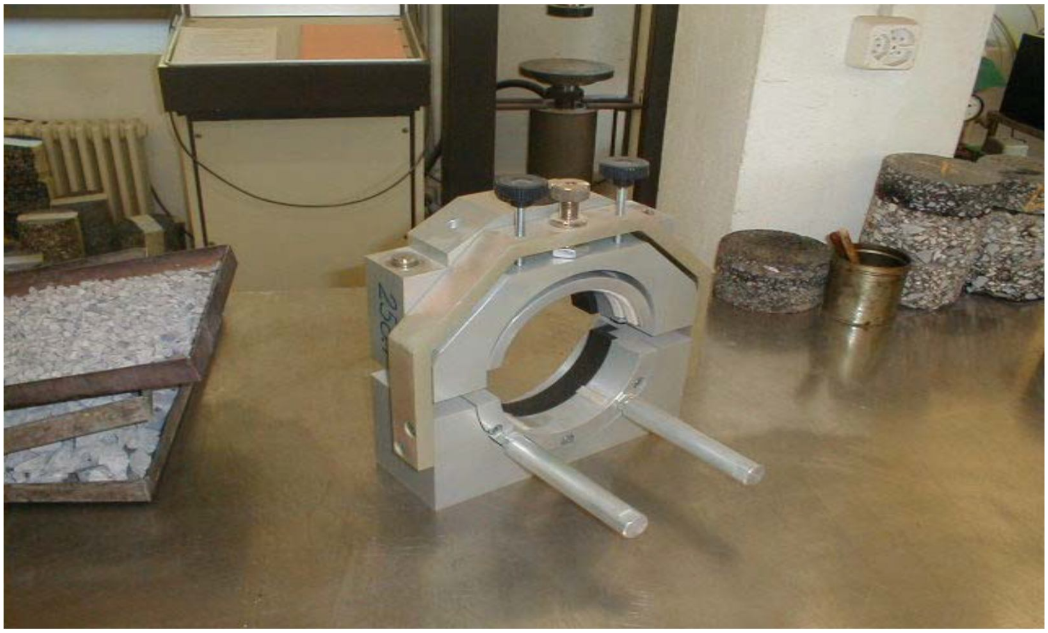


Figure 2.5 Swiss LPDS Tester (Buchanan and Woods 2004)

Florida Department of Transportation (FDOT) developed a device for evaluating the shear bond strength of tack coat at the interface of the asphalt layers. This shear tester was an attachment device which can be used in a universal testing machine or a Marshall Press. The specimens used for FDOT shear tester device having 150 mm diameter compacted in two composite layers or field core samples. Before performing the test, the specimens were conditioned at a temperature of 25±1°C for a minimum of 2 hours. The load application is strain controlled at a rate of 50.8-mm/min, which can be easily achieved in the Marshall Stability test apparatus. The specimens were placed inside the two ring attachment and a gap of 4.76 mm was provided between two rings. The shear strength was calculated by

$$S_B = \frac{4P_{max}}{D^2\pi} \qquad (2.2)$$

Where

S_B = shear strength (psi)

P_{max} = Maximum load applied (lbf)

D = Diameter of specimen (inches)

The observation was involved evaluation of several variables which affect the tack coat bonding strength such as application rate, surface condition, surface texture, and mixture type of field core specimens. The specimens were prepared by applying 0.0, 0.02, 0.05 and 0.08gal/yd.^{2} (0.00, 0.091, 0.226 and 0.362 L/m^2) as tack coat application rates. Based on their investigations, an application rate of 0.05 gal/yd.^{2} (0.266 l/m^2) was found to an optimum rate of application where the bond strength maximum. Also significant reduction of shear strengths was observed due to the presence of moisture at the interface. The shear strengths for fine graded mixtures were significantly lower as compared to coarse graded mixtures.

Figure 2.6 FDOT Shear Tester Device inside an MTS (Sutradhar, B. B., 2012)

In Italy Univarsita Politecnica Delle Marche Santagata et al. (1993) designed the ASTRA (Ancona Shear Testing research and Analysis apparatus) for observing the interlayer bond shear strength of bituminous paving layers. The system consist of a direct shear box to hold the cylindrical specimens of 100 mm diameter placed in two independent half-box and mounted on a movable table. A horizontal load is applied along the interface of double-layered specimens at a constant displacement rate of 2.5 mm/min until failure; in the meantime, a constant normal load is applied on top of the specimen as shown in figure. During the test process, the shear force, vertical displacement and the horizontal displacement were recorded. The study was conducted to observe the influence of tack coat type, temperature, and applied normal load, on the interlayer shear resistance. The study was concluded that the interface shear strength increased with an increase in normal stress for a given temperature and shear strength was found to increase with a decrease in temperature for a given normal stress. The square cross section of 100×100mm specimens was also tested on ASTRA.

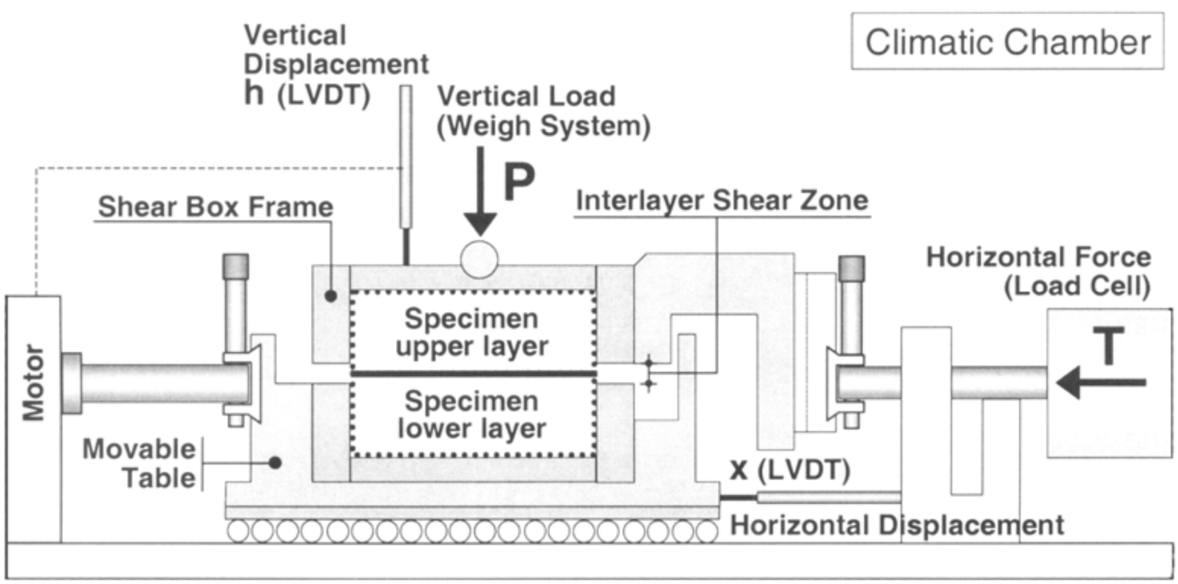


Figure 2.7 Schematic view of ASTRA device (Santagata et al., 2005)

National Center for Asphalt Technology (NCAT) developed a bond strength device was a shear type test and loading could be performed with a universal testing machine or a Marshall Press. There were a few modifications were made to the original version of the NCAT test device for improvement the capability of applying horizontal load as a normal pressure to the test specimens. The bond strength, S_B is calculated based on the maximum load as follows:

$$S_B = \frac{P_{max}}{A} \tag{2.3}$$

Where

S_B = bond strength (psi)

P_{max} = maximum load applied to the specimen (lbf)

A = cross-sectional area of test specimen (in^2)

West et al. (2005) conducted a two-phase observation included both laboratory and field phases for evaluating the bond strength between pavement layers. In the laboratory one, the following conditions were observed: two types of emulsion (CRS-2 and CSS-1) and a PG 64-22 asphalt binder; three residual application rates (0.02, 0.05, and 0.08 gal/yd^2) and two mix types [19 mm nominal maximum aggregate size (NMAS) coarse-graded and 4.75 mm NMAS fine-graded]. Interface bond strengths were evaluated using normal Superpave mix design specimens at three temperatures (10, 25, and 60°C) and three normal pressure levels (0, 10, and 20 psi). The main observations drawn from the laboratory study were as the temperature increased; bond strength decreased significantly for all tack coat types, application rates, and mixture types at all normal pressure levels. PG 64-22 exhibited higher bond strength as compared to the two emulsions, especially for the fine-graded mixture tested at high temperature. For the application rates observation, tack coats with low application rates generally provided high bond strength for the fine-graded mixture; however, for the coarse graded mixture, bond strength did not change much when application rate varied.

In the second phase, seven field observations were performed to evaluate the bond strength test with considering the same tack coat material used in phase one. Tack coat was sprayed on milled or un-milled pavement surface before the HMA overlay was placed and compacted. For the study using an emulsified asphalt tack coat material, the residual application rates were 0.03, 0.045, and 0.06 gal/yd^2 (0.15, 0.23 and 0.30 L/m^2). The tack coats were applied by three methods; hand wand sprayer, distributor truck spray bar and Novachip spreader. The main observations of the field study were milled HMA surfaces appeared to significantly enhance bond strength with a subsequent asphalt pavement layer and bond strengths in sections that used the Novachip spreader for application of tack coat were significantly higher than the other application method.

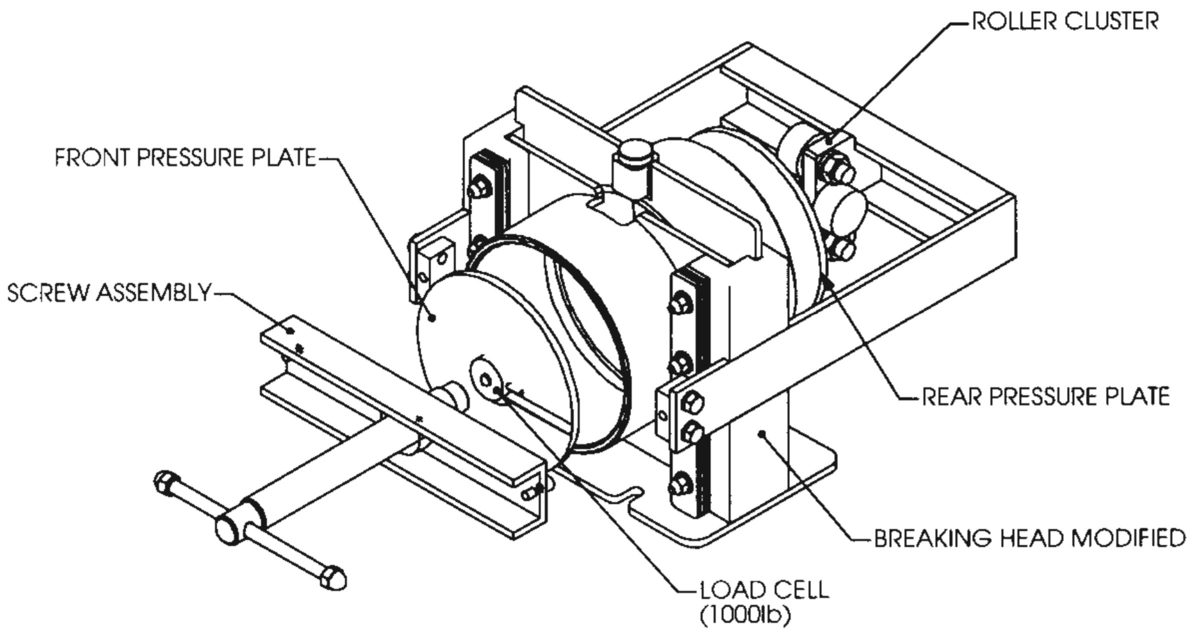


Figure 2.8 NCAT Bond Strength Device (West et al., 2005)

A Modified Torque Bond Tester was a relatively simple test device for evaluating the interface bond strength of bituminous paving layers was developed by Tashman et.al. (2006). Originally it was developed in Sweden for in-situ testing of asphalt interfaces. The pavement is cored deeper than the interface and a metal plate is glued to the top of the core specimen. A torque is applied to the top of the core until failure of interface because introducing of a twisting shear failure force at that place. The force/torque required to failure would indicate the strength of tack coat. The bond strength of the cored specimen is calculated using the following equation.

$$\tau = \frac{12M_x 10^6}{\pi D^3} \qquad (2.4)$$

Where

τ= Interface bond strength (kpa)

M= Maximum torque required to failure (N-m)

D= Diameter of the core (mm)

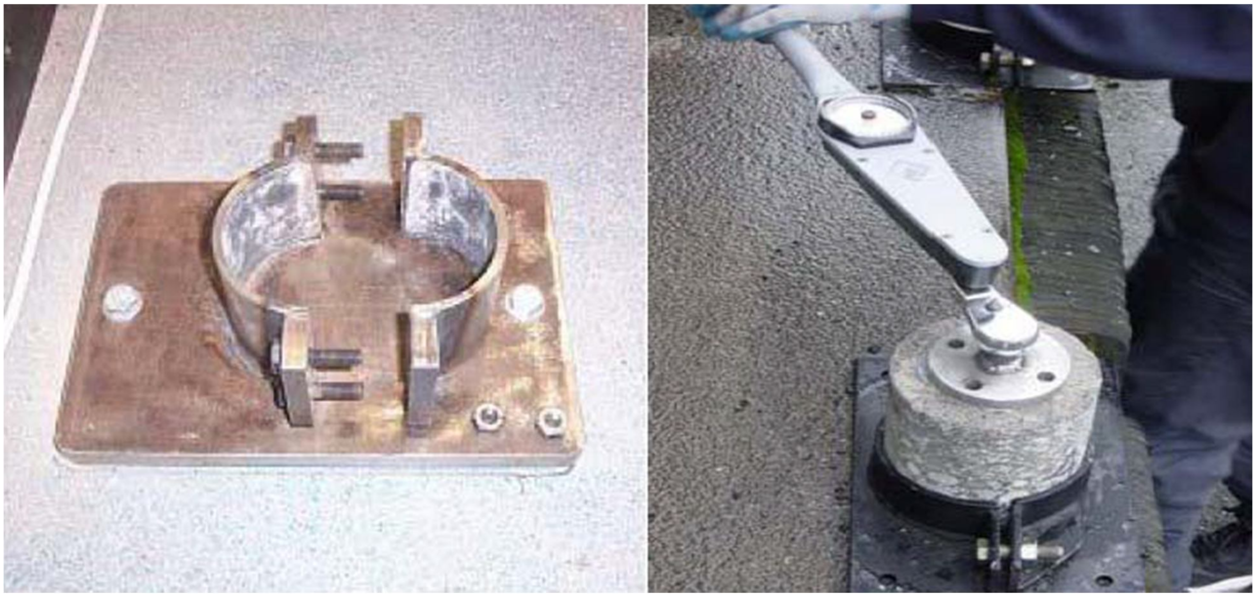


Figure 2.9 Torque Bond Tester with procedure (Tashman et al. 2006)

Miro et al. (2006) developed a device named as Laboratorio de Caminos de Barcelona (LCB) in the Road Research Laboratory of the Departament of Transportation of the Technical University of Catalonia. It was intended to measure the tangential stress resistance of tack coat. A cylindrical mould of 177.8mm height and 101.6mm internal diameter was used for LCB test. The asphalt layer was compacted about 100 or 110mm as first layer by using Marshall Compactor applying 100 compaction blows and allowed to be cool. On the upper of the specimen, tack coat was applied and the second layer was compacted. The test was conducted by placing the mould with the specimen horizontally over a base prepared with two supports 200mm apart. The cylindrical specimen is considered as a beam located over two supports such that the bonded interface is very close to one of the supports in order to avoid the formation of bending stress and the specimen fails due to shear stress only. The one part of the mould was resting on one support and upper layer of the specimen rests on other support proved a 5 mm gap to interface from mould top edge and supports shown in figure. The loading piston was placed over the mould, 100mm apart from the two supports by applying a constant deformation rate of 1.27mm/min. The load-deflection data were recorded by using a suitable data acquisition system.

$$\tau = \frac{\left(\frac{P}{2}\right)}{S} \tag{2.5}$$

Where

τ = Shear strength

P = Maximum failure load

S = Cross section of specimen

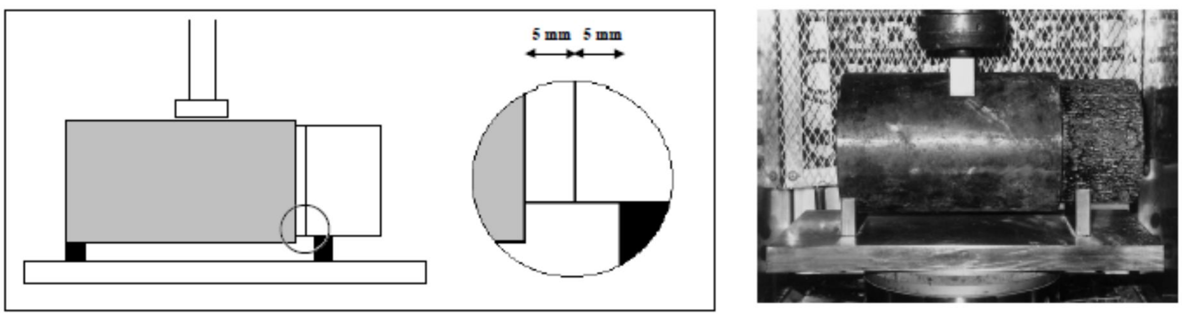


Figure 2.10 Schematic and actual view of LCB shear test (Miro et al., 2006)

Wheat M. (2007), in Kansas State University was developed a testing apparatus to investigate the influence of shear stress in different planes of the tack coat interface. The device consist of two supports, one hold the bottom part of the specimen and other one take responsibility for holding the top portion of the specimen. The test was performed under a sinusoidal loading at six different frequencies (25, 10, 5, 1, 0.5 and 0.1 Hz). The deflection between the two layers of specimens measured by two LVDTs which were connected to a suitable data acquisition system.

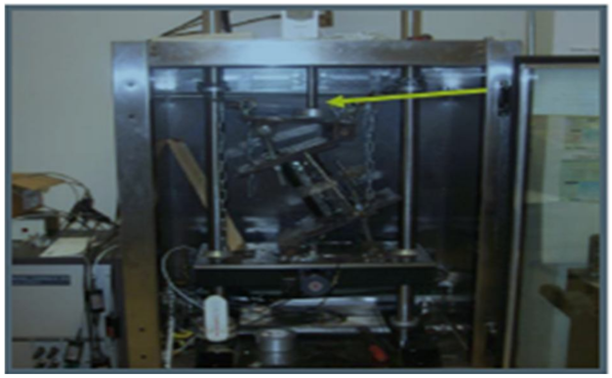


Figure 2.11 KSU shear tester (Wheat M., 2007)

In 2009, the Pennsylvania Department of Transportation fabricated a modified Marshall jig which consists of two hollow cylinders aligned horizontally from which one of the cylinders was fixed at the bottom of a base plate of the machine, while another one move vertically with minimal friction along four columns. During the test, a load was applied on a smooth horizontal strip located at the top of the movable cylinder of the attachment. The direct shear force applied vertically to the movable cylinder of the attachment. The direct shear force applied vertically to the movable cylinder at a constant rate of 50.8 mm/min until failure of the specimen. In this test, the specimen was placed in such a way that shearing of the specimen occurred along the interface of the two asphalt layers. The applied load and displacement of the moving cylinder were measured by a load cell and LVDT which were recorded by a data acquisition system.

Tony Kucharek et al. (2011) developed a Modified Marshall stability mould at Mcasphalt lab. One part of the mould is fixed at its bottom to a base plate, while the other semicircular sleeve can move vertically with minimum friction along the two guiding rods. A load of constant deformation at a rate of 50.8 mm/min is applied on a smooth horizontal stripe located on the top of the shear sleeve adjacent to the interface as shown in figure. This laboratory study was conducted on double-layered specimens prepared using 16 emulsions applied at 0.05, 0.1 and

0.15 Kg/m^2 to evaluate the influence of substrate characteristics . The study concluded that the rougher substrate revealed higher shear strength compared to the smooth surface.

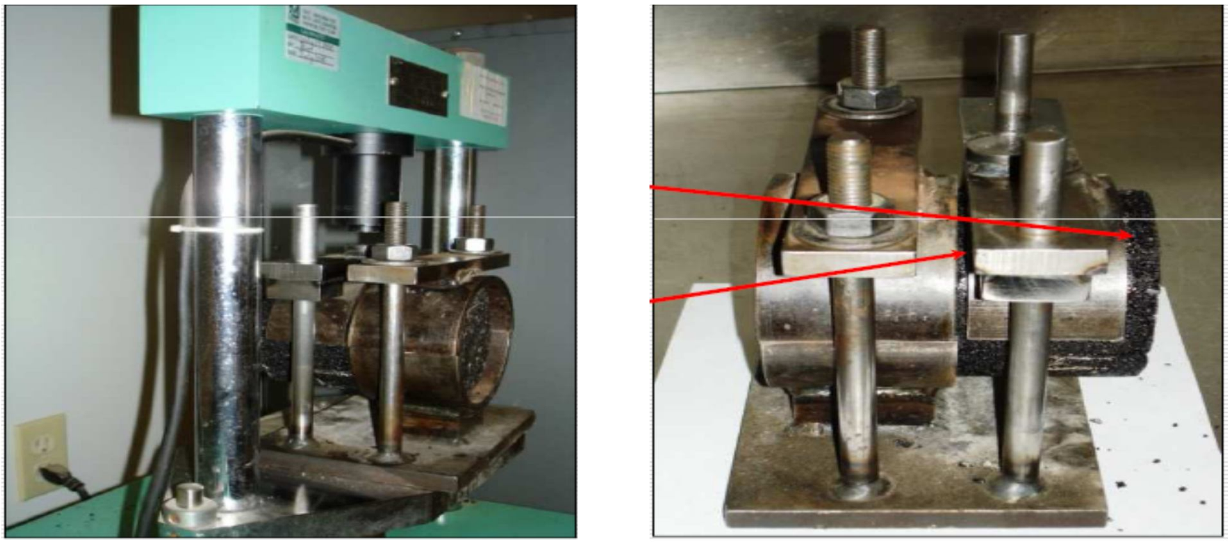


Figure 2.12 Shear-Testing device developed at McAsphalt Lab (Sutradhar, B. B., 2012)

2.3 Factors affecting the interlayer bond strength of pavement

Bituminous pavement structures are built in several layers with a certain degree of bonding at the interface, which is affected by different factors which could be either material related, or construction related. Existing literature clearly discloses the important factors which affecting the interlayer bond strength of the pavement layers including rate of displacement, tack coat type, tack coat application rate, testing temperature, normal pressure acts at the interface and setting time of it.

2.3.1 Influence of rate of displacement

The samples were tested at greater displacement/strain rates require a greater load to fail the joint of two layers because of the viscoelastic nature of a bituminous binder. Sholar et al. (2004)

concluded from the experiments that the core samples which tested an at a greater displacement rate exhibited a higher average failure shear strength (60 psi) compared to the samples tested at 0.75 in/min (38 psi).

2.3.2 Influence of tack coat type

Review of the above literature clearly specifies the use of hot bituminous binder, cutback bitumen or bituminous emulsions as tack coat materials. But now a day bitumen emulsion is most widely used as the tack coat material all over the world. Emulsified bitumen (bituminous emulsion) is a mixture of bituminous binder, water and emulsifying agent. The emulsifying agent can be soap, dust or colloidal clays.

The type of emulsifying agent used in the asphalt emulsion will determine whether the emulsion will be anionic or cationic. If the emulsifying agent is anionic, the asphalt droplet bears a negative charge. On the other hand, for a cationic emulsion, the asphalt droplet bears a positive charge. According to the Unified Facilities Guide Specification (UFGS) 02744N, the advantage of the slow-setting grades over the rapid-setting grades is that they can be diluted. Diluted emulsions are reported to give better results because of the following reasons

i. Diluted emulsion provides the extra volume required for the tack coat distributor to function at normal speed especially at lower application rates.

ii. Diluted emulsion allows for a more uniform application as it flows easily from the distributor at ambient temperatures. However, for a longer setting period of slow setting emulsions compared to rapid setting emulsions, it is not desirable to use slow setting emulsions as a tack coat in relatively cool weather, at night, or when there is a narrow construction window.

The International Bitumen Emulsion Federation (IBEF, 1999) conducted a world-wide survey of the use of tack coats. The survey reported that cationic emulsions are the most common tack coat material, with some use of anionic emulsions.

Paul and Scherocman (1998) in the United States, made a survey on use of tack coat and gather information that the most common among them are SS-1, SS-1h, CSS-1, and CSS-1h. Some states like California, Florida, and Vermont used the rapid setting type of emulsions such as RS-1 and RS-2. Florida and Georgia were the only states those used paving grade asphalts (AC-5, AC-20, and AC-30) as tack coats at the time of the survey.

2.3.3 Influence of tack coat application rate

The tack coat application rate refers to the quantity of tack coat material applied per unit surface area. An excessive tack coat may promote to slippage at the interface while too little may result in de-bonding problems between two bituminous paving layers. Therefore, it is important to

estimate the optimum amount of tack coat that will produce the best performance in the bonding at the joint. To achieve a proper interface bond, pavement surfaces with different conditions (e.g., new, old, or milled) requires different tack coat application rates. Normally, a slow - setting grade of emulsions required higher application rates than a rapid-setting grade of emulsions, and rapid-setting grade emulsions required higher application rates than paving grade bituminous binders. Besides, that dense and gap-graded HMA overlay requires less tack coat as compares to open-graded overlays.

An international survey, conducted by the International Bitumen Emulsion Federation (1999) indicated that the residual bitumen content varied from 0.026 to 0.089gal/yd^2 for tack coats applied over conventional bituminous surfaces.

In the United States, a survey conducted by Paul and Scherocman (1998), reported that the residual application rates of the emulsions varied between 0.01 and 0.06 gal/yd^2, depending on the type of surface for application. The residual bitumen contents, as specified in The Hot-Mix Asphalt Paving Handbook (1989) should range from 0.04 to 0.06 gal/yd^2. As compare to open-textured surfaces, the requirement of tack coat is less for tight or dense graded surfaces. Also bleeding or flushed surfaces require less tack coat than surfaces that are dry and aged. The requirement of residual asphalt is even more for a milled surface because of the increased specific surface area, up to 0.08gal/yd^2. The requirement is only half as much residual asphalt typically for new HMA layers, 0.02gal/yd^2.

Mohammad et al. (2002) recommended an optimum residual rate of 0.02gal/yd^2 by conducting an experiment over interface of the two bituminous layers using the Simple Shear Test on one type of HMA pavement.

As per the section "Proper Tack Coat Application (2001)" of the Technical Bulletin published by the Flexible Pavements of Ohio, the recommended typical tack coat application rates for various pavement types using a slow-setting asphalt emulsions (SS1, SS1-h) are shown in Table 2.1.

Table 2.1 Recommended tack coat application rates in Ohio

Pavement Condition	**Application Rate (gal/yd^2)**		
	Residual	**Undiluted**	**Diluted (1:1)**
New HMA	0.03-0.04	0.05-0.07	0.10-0.13
Oxidized HMA	0.04-0.06	0.07-0.10	0.13-0.20
Milled Surface (HMA)	0.06-0.08	0.10-0.13	0.20-0.27
Milled Surface (PCC)	0.06-0.08	0.10-0.13	0.20-0.27
Portland Cement Concrete	0.04-0.06	0.07-0.10	0.13-0.20

According to the tack coat guidelines of the Construction Procedure Bulletin (2003) of the California Department of Transportation, the recommended application rates for different types of tack coats and pavement conditions, which are used in the state of California as shown in Table 2.2

Table 2.2 Recommended Tack Coat Application Rates Used in California

Type of Overlay	**Type of Surface**	**Slow Setting (gal/yd^2)**	**Rapid Setting (gal/yd^2)**	**Paving Asphalt (gal/yd^2)**
HMA	Dense, Tight Surface (e.g., Between lifts)	0.044-0.077	0.022-0.044	0.011-0.022
	Open Textured or Dry, Aged Surface (e.g., Milled surface)	0.077-0.199	0.044-0.088	0.022-0.055
Open Graded HMA	Dense, Tight Surface (e.g., Between lifts)	0.055-0.110	0.022-0.055	0.011-0.033
	Open Textured or Dry, Aged Surface (e.g., Milled surface)	0.110-0.243	0.055-0.121	0.033-0.066

2.3.4 Influence of testing temperature

It was observed from the review of the laboratory studies conducted by various Researchers and Highway agencies that the testing temperature had given the most significant impact on the bond strength. As test temperature increases interlayer bond strength decreases due to reduced stiffness of tack coat material. The study conducted by West et al. (2005), reported that, the average bond strength values were 2.3 times greater at 10º C compared to 25º C; while the average bond strength values were 1/6 times lesser at 60º C compared to 25º C.

2.3.5 Influence of normal pressure

Numbers of laboratory studies were conducted by varied the normal pressure application to samples; all concluded that as normal pressure increases interlayer bond strength increases especially at higher temperature. At higher temperatures, the effect of internal friction on bond strengths were more than the tack coat materials and application rates, and the internal friction is dependent on normal load and surface texture of the layers. At intermediate and low temperatures, bond strength was not very sensitive to the normal pressure levels.

2.3.6 Influence of tack coat curing time

When water separates from the emulsion due to evaporation and the color of the tack coat begins to change from brown to black, the tack coat is set to break. Normally the color of bituminous emulsions is brown. When water evaporates from it, it becomes deep black. Moreover, when the water has completely separated from the emulsion, what remains behind is a thin film of bitumen binder on the pavement surface.

Paul and Scherocman (1998) obserced from their survey of state DOTs on tack coat practices that curing period between tack coat application and overlay paving was generally after the emulsions had broken. The majority of the states had no specifications on maximum setting time. Some of the states had a minimum setting time criteria which varies from 15 minutes to some hour depending upon the tack coat type.

2.4 Critical Reviews

Several organizations and several researchers were reported in the preceding paragraphs had developed and studied on various devices with various testing methodologies and evaluated the bond strengths of the interlayer of the bituminous pavement. Tack coats should be applied in an optimum quantity in a thin layer and should uniformly cover the entire surface of application area. Too little amount of tack coat would be as good as no tack coat and would fail to provide a sound interface bond. On the other hand, excess tack coat can cause slippage failure. The application rate must be selected based on the texture of the surface receiving the tack coat.

Chapter III

Experimental Methodology

Introduction

Methodology

Materials Used

Preparation of Samples

Fabrication of simple attachment to measure the Interlayer Bond Strength

3.1 Introduction

This chapter describes the experimental works carried out for this study of interlayer bond strength between two bituminous paving layers. This chapter has been divided into two parts. First part discusses the collection of materials which are used for preparing the composite cylindrical specimens (aggregates, bitumen, and emulsions) and second part described by the testing of the specimens by using a fabricated simple attachment which has been easily mounted on Modified Marshall Apparatus. For the study two different types of bituminous layer specimens were prepared with 100 mm total height and 101 mm in diameter. The specimens were prepared with varying different types of tack coat, bitumen as a tack coat also without using any tack coat. This investigation also observed dissimilarities in bond strength due to variations in their setting time and duration of compaction between two layers.

3.2 Methodology

The experimental methodology adopted in the study consisted of evaluating the maximum interlayer bond strength of the two types of bituminous layer combinations (DBM/BC and BM/SDBC). In this experimental method, the specimens were subjected to direct shear force applied at a constant rate of displacement of 50.8 mm/min until the failure of the specimens. A customized simple device referred to the modified Marshall test apparatus was fabricated for the testing of the double layer composite bituminous samples for evaluation of interlayer bond strength. The methodology adopted for this project is shown in figure 3.1.

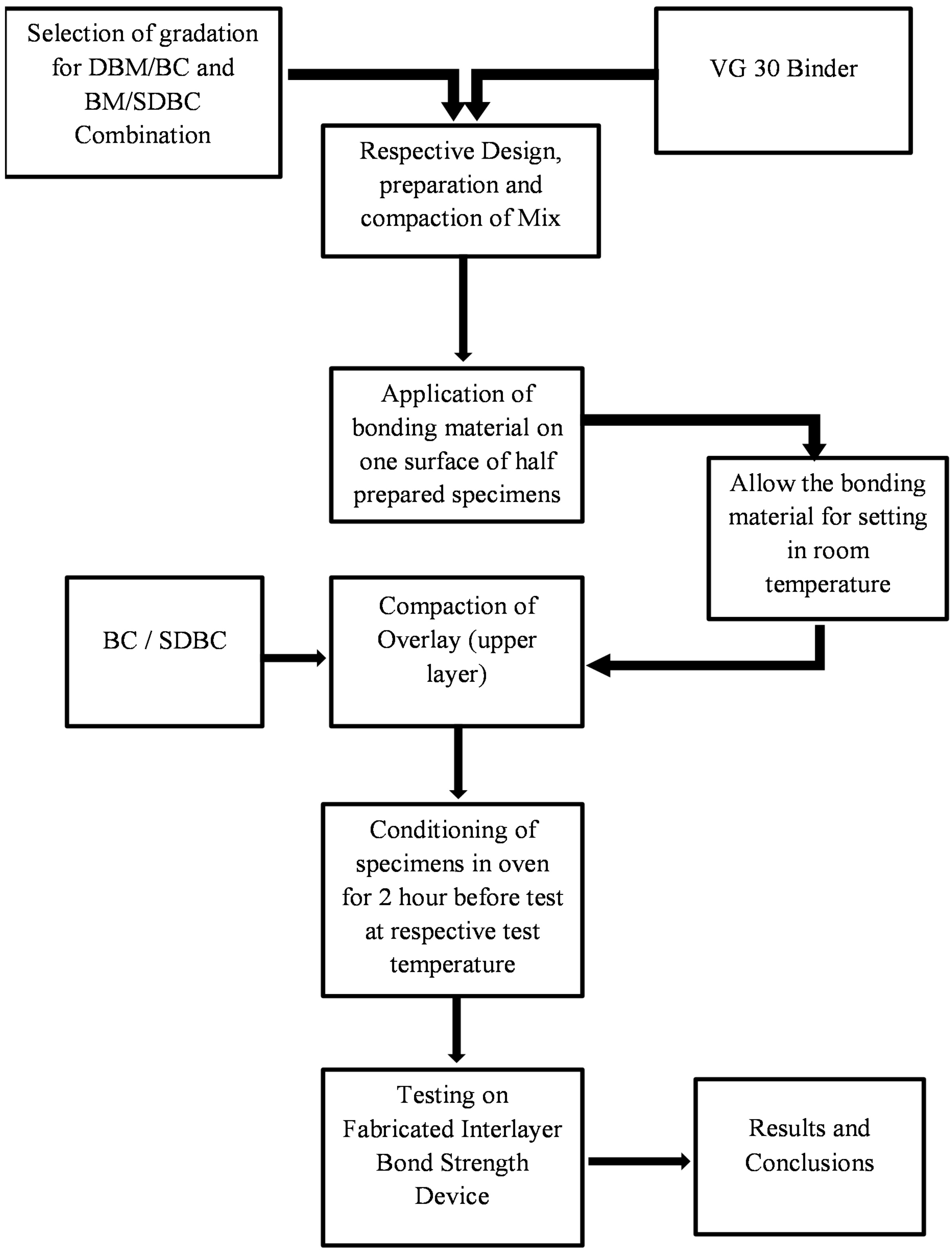


Figure 3.1 Methodology of the experimental work

3.3 Materials Used

3.3.1 Aggregates

This laboratory case study consists of two types bituminous layer of cylindrical specimens. One has been prepared with composite of, lower layer as dense bituminous macadam (DBM) and upper one bituminous concrete (BC). Another type has been prepared with bituminous macadam (BM) as a base course (lower layer) with semi dense bituminous concrete (SDBC) as an overlay. For preparing two bituminous composed layers aggregates were graded as per Ministry of Road Transport and Highways (2001) given in Table 3.1, Table 3.2, Table 3.3 and Table.3.4 respectively. The DBM and BM mixes, which use relatively larger size aggregate, are not only stiff or stable but also are economical because they use relatively lower bitumen contents and need less breaking and crushing energy or effort. BC and SDBC mix with smaller aggregate in the other way having relatively higher bitumen contents, which not only impart high flexibility but also increase their durability. The aggregates shall be clean, hard, durable, cubical shape, free from dust and friable matter, organic or other deleterious matter. The coarse aggregates are crushed gravel hard material must be retained on 4.75 mm sieve and fine aggregates must be passed in 4.75 mm sieve and retained on a 75 micron sieve. MORT&H recommended 25 mm nominal maximum aggregate size (NMAS) for DBM Base Course and 13 mm NMAS for BC Binder Course. It also recommended 19 mm NMAS for BM base course and 13 mm NMAS for SDBC course. The specific gravity of aggregates used for preparing the specimens in the laboratory has been found 2.80. The physical properties of the aggregates which found in laboratory were given in below table 3.5 .

3.3.2 Filler

Portland slag cement (Grade 43) collected from local market passing 0.075 mm IS sieve was used as filler material to increase the binding property between the aggregates in the preparation of specimens. Its specific gravity has been found in laboratory 3.0.

Table 3.1 MORTH gradation for DBM (NMAS 25mm)

BIS Sieve (mm)	Percent Passing	
	Specification Grading	Grading adopted
37.5	100	-
26.5	90-100	95
19.0	71-95	83
13.2	56-80	68
4.75	38-54	46
2.36	28-42	35
0.300	7-21	14
0.075	2-8	4
Binder Content % by weight	Min. 4.5	5

Table 3.2 MORTH gradation for BC (NMAS 13 mm)

BIS Sieve (mm)	Percent Passing	
	Specification Grading	**Grading adopted**
19.0	100	-
13.2	79-100	89.5
9.5	70-88	79
4.75	53-71	62
2.36	42-58	50
1.18	34-48	41
0.600	26-38	32
0.300	18-28	23
0.150	12-20	16
0.075	4-10	7
Binder Content % by weight	5-7	7

Table: 3.3 MORTH gradations for BM (NMAS 19 mm)

BIS Sieve (mm)	**Percent Passing**	
	Specification Grading	**Grading adopted**
26.5	100	-
19.0	90-100	95
13.2	56-88	72
4.75	16-36	26
2.36	4-19	11.5
0.300	2-10	6
0.075	0-8	4
Binder Content % by weight	3.3-3.5	3.5

Table: 3.4 MORTH gradations for SDBC (NMAS 13 mm)

BIS Sieve (mm)	**Percent Passing**	
	Specification Grading	**Grading adopted**
19.0	100	-
13.2	90-100	95
9.5	70-90	80
4.75	35-51	43
2.36	24-39	31.5
1.18	15-30	22.5
0.300	9-19	14
0.075	3-8	5.5
Binder Content % by weight	Min. 4.5	5

Table 3.5 Physical properties of aggregates

Property	Test Method	Test Result
Aggregate Impact Value (%)	IS: 2386 (Part-IV)	14.28
Aggregate Crushing Value (%)	IS: 2386 (Part-IV)	13.02
Los Angeles Abrasion Value (%)	IS: 2386 (Part-IV)	18
Flakiness Index (%)	IS: 2386 (Part-I)	18.83
Elongation Index (%)		21.50
Specific Gravity	IS: 2386 (Part-III)	2.75
Water Absorption (%)	IS: 2386 (Part-III)	0.13

3.3.3 Binder

During this investigation VG 30 bitumen collected from local source used as binder for preparing the specimens. Some common types of tests were performed to determine the important physical properties of these binders. The physical properties thus obtained are summarized in Table 3.6 (Sutradhar, B. B.. 2012).

3.3.4 Tack Coat

The tack coat materials selected for this study include two emulsions CMS-2 and CRS-1. Standardized tests were conducted to determine their physical properties as summarized in Table 3.7 (Sutradhar, B. B.. 2012).

Table 3.6: Physical properties of VG 30 bitumen binder

Property	Test Method	Test Result
Penetration at 25°C	IS : 1203-1978	67.7
Softening Point (R&B), °C	IS : 1205-1978	48.5
Viscosity (Brookfield) At 160°C, CP	ASTM D 4402	200

Table 3.7 Physical properties of Tack Coats

Property	Test Method	Emulsion Type	Test Results
Viscosity by Saybolt Furol Viscometer, seconds: At 50^0 C	ASTM D 6934	CRS-1	37
		CMS-2	114
Density in g/cm^3	As per Chehab et al. (2008)	CRS-1	0.986
		CMS-2	0.986
Residue by evaporation, percent	ASTM D 244	CRS-1	61.33
		CMS-2	67.59
Residue Penetration 25^0 C/100 g/5 Sec	IS : 1203-1978	CRS-1	86.7
		CMS-2	106.7
Residue Ductility 27^0 C cm	IS : 1208-1978	CRS-1	100+
		CMS-2	79

3.4 Preparation of Samples

The specimens were prepared to evaluate the interlayer bond strength between the bituminous paving layers either be made in the laboratories or collect from the field as a core. The laboratories prepared samples were mixed according to the Marshall procedure specified in ASTM D1559 and follows MORT&H grading of coarse and fine aggregate for both two types of composite specimens. The specimens are prepared for evaluation of bond strength having 101 mm diameter and total height of 100 mm with the help of a special fabricated mold. These samples were compacted into two layers; DBM and BM have 60mm as base course and top layer as BC and SDBC of 40mm height respectively. In between these two layers a layer of tack coat has applied. VG-30 binder has used for mixing of the base and surface courses in 0.075mm passing cement was used as filler to increase the binding property .

The specimens consisted of two layers and the tack coat are applied between them. The study also carried out with bitumen used as tack coat material and with no tack coat used in between the two bituminous layers. Graded aggregates were sampled and kept them in an oven at 160^0C for at least two hours before mix with a binder to form a design mix. The lower half of the specimen called as base course was prepared by compacted the design mix to a required height of 60 mm giving 75 blows with Marshall Hammer . Once the lower layer compacted by the same number of blows on both sides; it allowed to cool at room temperature for a few days. Then a layer of stiky material (tack coat and bitumen) has been applied at one surface of the previously compacted specimen. The amount of emulsions was calculated multiplying the application rates with the surface area of the specimen. The rate of application of tack coat was selected as per MORT&H (2001) specified as given in Table.3.8 .

Table 3.8 Rate of application of Tack Coat as per MORT&H Specification

Type of Surface	Quantity in Kg/m^2 area
Normal bituminous surface	0.20 to 0.25
Dry and hungry bituminous surface	0.25 to 0.30
Granular surface treated with primer	0.25 to 0.30
Non bituminous surface	-
Granular base (not primed)	0.35 to 0.40
Cement Concrete pavement	0.30 to 0.35

When the specimens have been tacked, they were allowed to cure until setting/breaking completed in a dust-free environment. The minimum setting period of emulsions is generally estimated by visual observation. Normally tack coat was brown in color, but when the water evaporates from it; its color became deep black. This process is called setting of emulsion. After setting of emulsions, it left a thin layer of bitumen residue which work as a glue between two layers as result good bond was formed. In the study two types of emulsions have been used, CRS-1 and CMS-2. CRS means cationic rapid setting and CMS means cationic medium setting emulsion. Normally rapid setting emulsion set very fast, less than half an hour. When bitumen used as sticky material in the place of tack coat, application rates consider as per MORTH specification and setting of its normally varied from half an hour to one hour maximum for creating a better bonding between two layers.

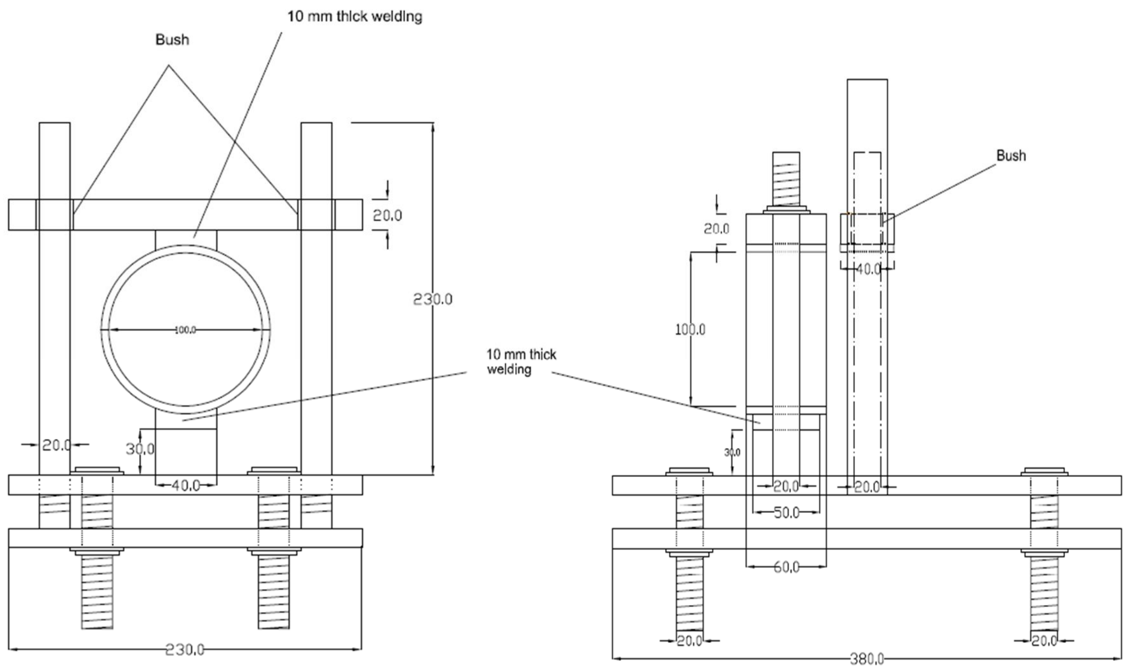
Once the application and curing of the tack coat was completed on one surface of the lower layer of specimens, the loose design mix for top layer was placed over it. Total required height for the samples was deserved by compacted the loose mix with the help of Marshall Hammer applied

100 numbers of blows. All prepared specimens were allowed to cure at room temperature for a few days before testing. The specimens prepared without any tack coat, the top layer was compacted as soon as possible after the lower layer compaction. For observing the variation in bond strength without using any tack coat some time gap may be maintained between compaction of two layers.

After a few days of curing at room temperature specimens have been fully prepared for the test. Before the testing procedure was carried out these specimens were cured in an oven at different temperature (25^0, 30^0, 35^0 and 40^0C) for two hours. The specimens were tested on fabricated bond strength attachment mounted on a modified Marshall test apparatus.

3.5 Fabrication of simple attachment to measure the Interlayer Bond Strength

In the study, the laboratory prepared specimens were tested by using a fabricated attachment fitted to modified Marshall apparatus. This device was designed based on the shearing apparatus at McAsphalt Lab (Kucharek,T et. Al., 2011). The device was designed for 101 mm diameter field core or laboratory prepared samples. The device consisted of two parts for holding the specimen's at upper and lower. One was a U-shape for hold the upper part (40 mm) could move freely with minimum friction along with two guiding rods fixed on the top of the base plate and another one clamping the lower half of the specimen. The schematic diagrams of the fabricated Interlayer Bond Strength device has shown in the figure 3.2 and the photographic views shown in figure 3.3. The vertical load was transferred to the U shape plate for shear the specimens at a constant rate of 50.8 mm/min (2 in/min).



(a) Front view

(b) Side view

Figure 3.2 Schematic diagrams of the fabricated Interlayer Bond Strength device

Figure 3.3 Photographic views of the fabricated Interlayer Bond Strength device

Chapter IV

Results and Discussions

Introduction

Laboratory Test Results

Overall performance of Interlayer Bond Strength

4.1Introduction

The experimental test was conducted for observing the interface bond strength between two types of bituminous paving layers carried out in the cylindrical laboratory prepared specimens having 100 mm diameter and 100 mm total height which was tested on a fabricated attachment fitted to the Marshall Loading frame. The results were obtained at four different test temperature 25^0, 30^0, 35^0, and 40^0C with two type tack coat CMS-2 and CRS-1 varying with different application rate. Also the bond strength was evaluated by using bitumen as a tack coat with various application rates and without using any tack coat. The CMS-2 type emulsion was observed considering three setting time 6, 9 and 12 hours and in CRS-1 type 0.5, 1 and 1.5 hours. The curing time for bitumen used in place of tack coat, before applying the overlay taken as no curing time, half an hour and one hour. In the study shear strength was evaluated at the interface between bituminous macadam (BM) and semi dense bituminous concrete (SDBM) type flexible paving layers considered with CMS-2 and CRS-1 bitumen emulsions.

The interface bond shear strength was calculated by (Sutradhar, B. B., 2012)

$$\text{IBSS} = \frac{F_{max}}{A} \tag{4.1}$$

Where IBSS: Interface bond shear strength (kPa)

F_{max}: Maximum load required to shear the specimens (kN)

A: Cross sectional area of the specimen (m^2) = $\pi \times R^2$

R: Radius of the specimens (m)

4.2 Laboratory Test Results

The results of various tests conducted to evaluate the interlayer bond strength in various types of combinations are presented below.

4.2.1 Interlayer Bond Strength for Dense Bituminous Macadam (DBM) and Bituminous Concrete (BC) Combination

4.2.1.1 Variation of ILBS with rate of application for CRS-1 type tack coat at various setting times

The test results of bond strength with various application rates in case of CRS-I type tack coat cured at different setting times are presented in the following paragraphs.

In Table 4.1 present the average interlayer bond strength when setting time is 0.5 hours. The highest bond strength values are observed at application rate of 0.25 Kg/m^2 at all test temperatures for te CRS-1 type of tack coat.

Table 4.1 ILBS of CRS-1 type tack coat (Considering 0.5 hour setting time)

Type of Tack Coat	**Application rate (Kg/m^2)**	**Average ILBS at different test temperature (kPa)**			
		25^{0}C	**30^{0}C**	**35^{0}C**	**40^{0}C**
CRS-1	0.2	691.37	530.09	411.26	286.90
	0.25	716.83	635.35	460.49	323.83
	0.3	609.88	511.42	332.31	249.55

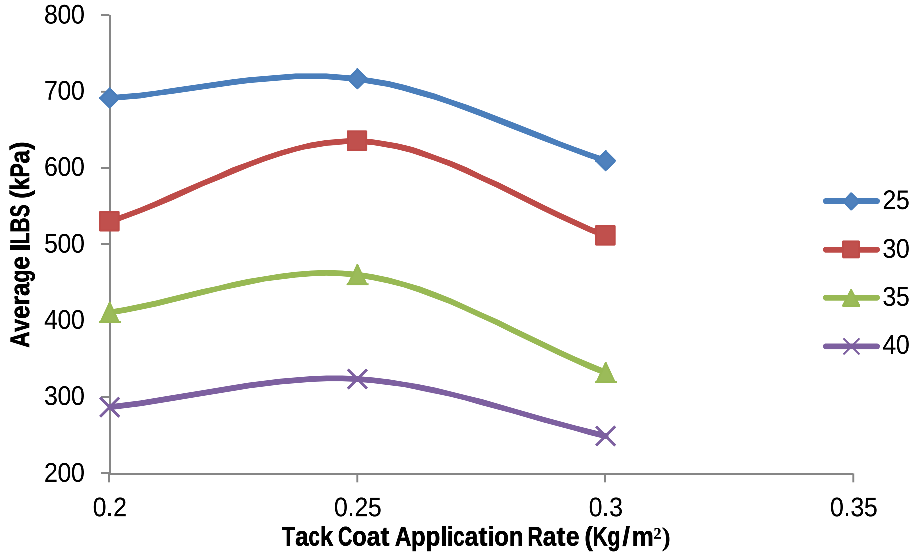


Figure 4.1 Relationship between Average ILBS and Tack Coat Application Rate at different test temperature when setting time is 0.5 hours for the CRS-1 type of tack coat.

From the figure 4.1 it is observed that the maximum interlayer bond strength was found at a 0.25 Kg/m^2 application rate in all test temperatures when the setting time considered as 0.5 hours and the bond strength was decreased when test temperature and application rate increased.

In Table 4.2 present the average interlayer bond strength when setting time is 1 hour. The highest bond strength values are observed at application rate of 0.25 Kg/m^2 at all test temperatures for the CRS-1 type of tack coat.

Table 4.2 ILBS of CRS-1 type tack coat (Considering 1 hour setting time)

Type of Tack Coat	**Application rate (Kg/m^2)**	**Average ILBS at different test temperature (kPa)**			
		25^{0}C	**30^{0}C**	**35^{0}C**	**40^{0}C**
CRS-1	0.2	874.71	556.40	443.51	311.94
	0.25	892.96	773.28	543.25	344.20
	0.3	805.11	548.76	378.15	293.27

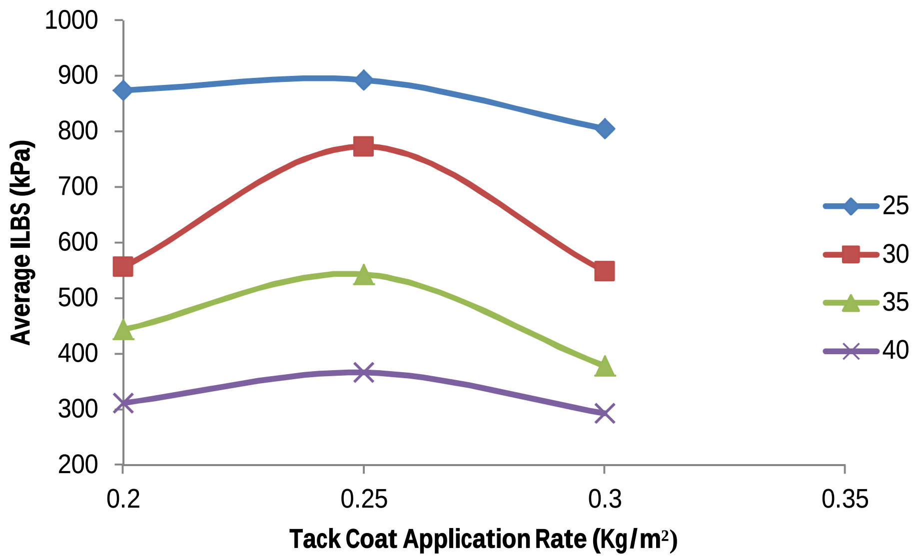


Figure 4.2 Relationship between Average ILBS and Tack Coat Application Rate at different test temperature when setting time is 1 hour for the CRS-1 type of tack coat.

From the figure 4.2 it is observed that the maximum interlayer bond strength was found at a 0.25 Kg/m2 application rate in all test temperatures when the setting time considered as 1 an hour and the bond strength was decreased when test temperature and application rate increased.

In Table 4.3 present the average interlayer bond strength when setting time is 1.5 hours. The highest bond strength values are observed at application rate of 0.25 Kg/m^2 at all test temperatures for the CRS-1 type of tack coat.

Table 4.3 ILBS of CRS-1 type tack coat (Considering 1.5 hour setting time)

Type of Tack Coat	Application rate (Kg/m^2)	Average ILBS at different test temperature (kPa)			
		25^{0}C	30^{0}C	35^{0}C	40^{0}C
CRS-1	0.2	760.97	535.61	423.99	293.27
	0.25	842.88	662.93	499.53	337.41
	0.3	748.66	522.88	361.60	287.33

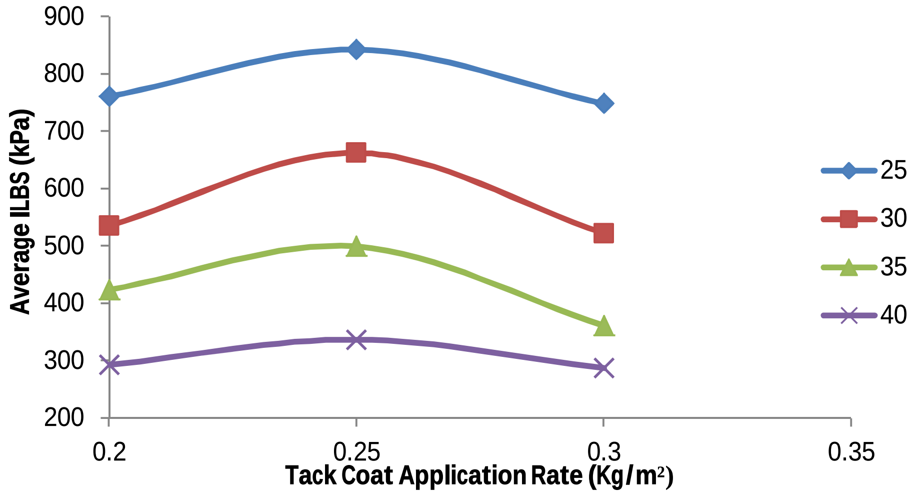


Figure 4.3 Relationship between Average ILBS and Tack Coat Application Rate at different test temperature when setting time is 1.5 hours for the CRS-1 type of tack coat.

From the figure 4.3 it has been observed that the maximum interlayer bond strength was found at a 0.25 Kg/m^2 application rate in all test temperatures when the setting time considered as 1.5 hour and bond strength was decreased when test temperature and application rate increased.

4.2.1.2 Comparisons of Average ILBS and Tack Coat Application Rates at different test temperatures with various setting times of the CRS-1 type of tack coat.

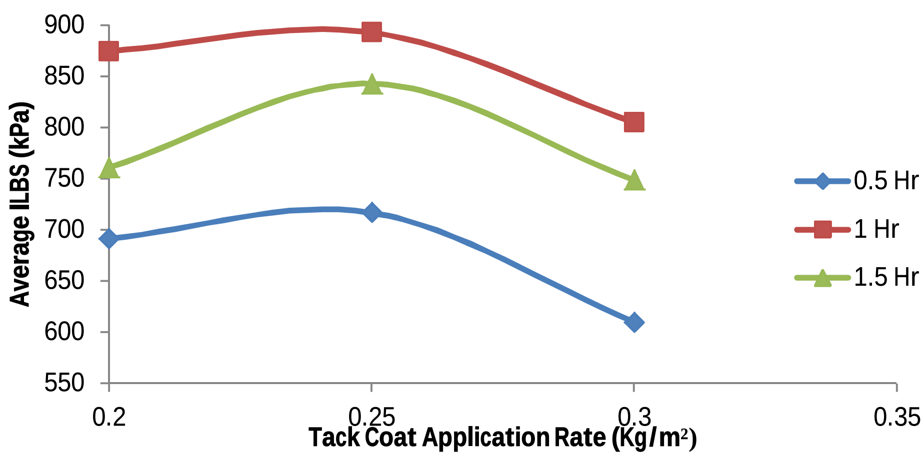


Figure 4.4 Relationships between Average ILBS and Tack Coat Application Rates at 25^{0}C for the CRS-1 type of tack coat.

Figure 4.4 presents the variation in the mean interlayer bond strength with application rates and variation in setting times obtained for CRS-1 type tack coat applied over a clean DBM surface. The highest bond strength was observed in setting time of 1 hour as compared to others at test temperature 25^{0}C with an application rate of 0.25 Kg/m^2.

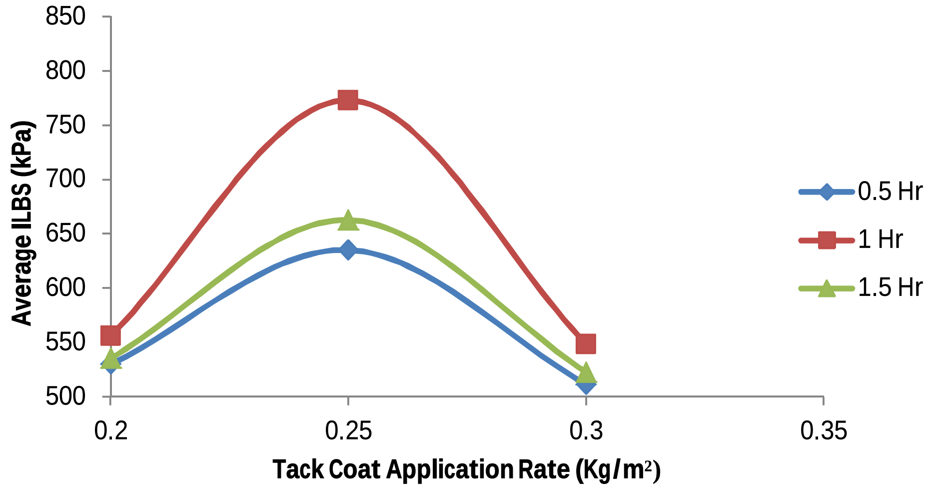


Figure 4.5 Relationships between Average ILBS and Tack Coat Application Rates at 30^{0}C for the CRS-1 type of tack coat.

Figure 4.5 presents the variation in the mean interlayer bond strength with application rates and variation in setting times obtained for CRS-1 type tack coat applied over a clean DBM surface. The highest bond strength was observed in setting time of 1 hour as compared to others at test temperature 30^{0}C with an application rate of 0.25 Kg/m^2.

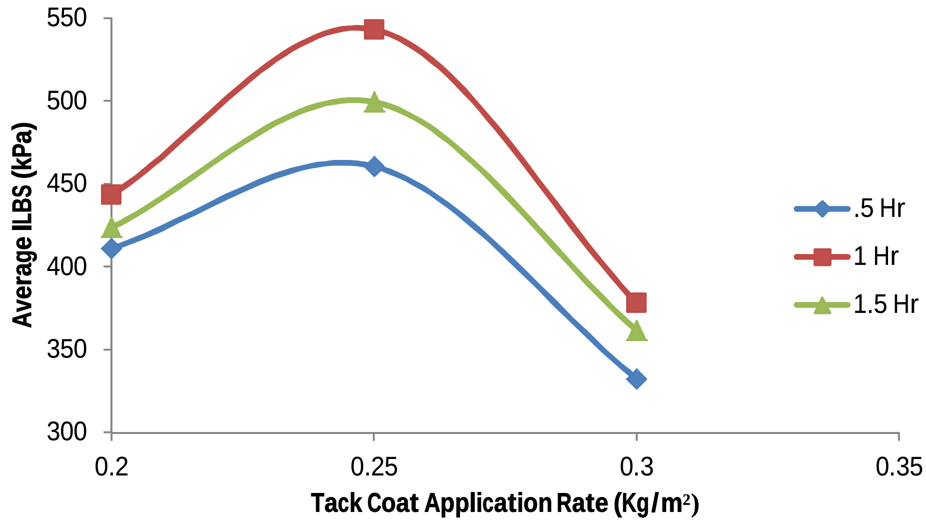


Figure 4.6 Relationships between Average ILBS and Tack Coat Application Rates at 35^0C for the CRS-1 type of tack coat.

Figure 4.6 presents the variation in the mean interlayer bond strength with application rates and variation in setting times obtained for CRS-1 type tack coat applied over a clean DBM surface. The highest bond strength was observed in setting time of 1 hour as compared to others at test temperature 35^0C with an application rate of 0.25 Kg/m^2.

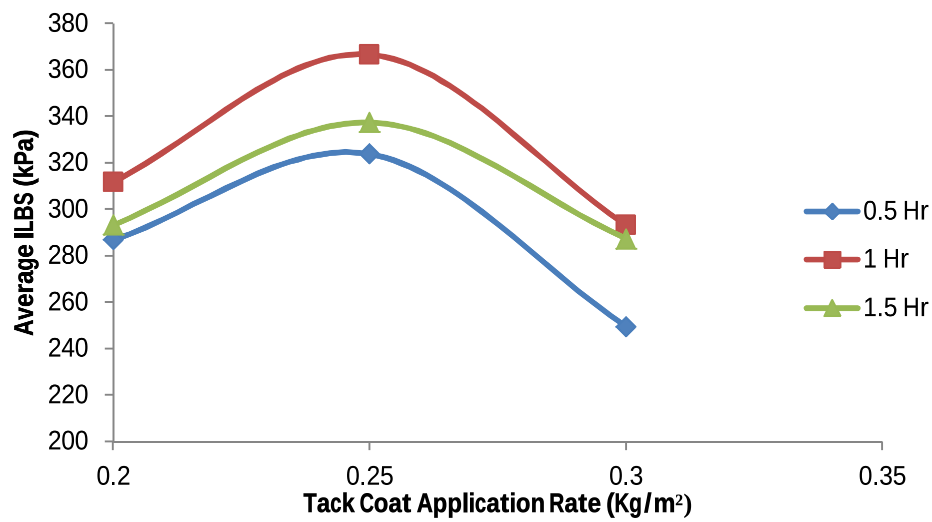


Figure 4.7 Relationships between Average ILBS and Tack Coat Application Rates at 40^0C for the CRS-1 type of tack coat.

Figure 4.7 presents the variation in the mean interlayer bond strength with application rates and variation in setting times obtained for CRS-1 type tack coat applied over a clean DBM surface. The highest bond strength was observed in setting time of 1 hour as compared to others at test temperature 40^0C with an application rate of 0.25 Kg/m^2.

From the figures 4.4 to 4.7 it is observed that in all test temperatures the maximum interlayer bond strength was found at 0.25 Kg/m^2 application rate when setting time for rapid setting emulsions (CRS-1) taken 1 hour as compared to 0.5 and 1.5 hours. The highest bond strength was obtained at 25^0C and the strength was decreased when the test temperature increases.

4.2.1.3 Variation of ILBS with rate of application for CMS-2 type tack coat at various setting times

In Table 4.4 present the average interlayer bond strength when setting time is 6 hours. The highest bond strength values are observed at application rate of 0.15 Kg/m^2 at all test temperatures for the CMS-2 type of tack coat.

Table 4.4 ILBS of CMS-2 type tack coat (Considering 6 hour setting time)

Type of Tack Coat	**Application rate (Kg/m^2)**	**Average ILBS at different test temperature (kPa)**			
		25^0C	**30^0C**	**35^0C**	**40^0C**
CMS-2	0.1	962.57	691.37	479.16	318.01
	0.15	1013.50	704.10	535.16	342.93
	0.2	918.43	697.73	497.84	311.94
	0.25	887.45	672.27	423.56	255.92
	0.3	729.14	616.67	392.58	230.88

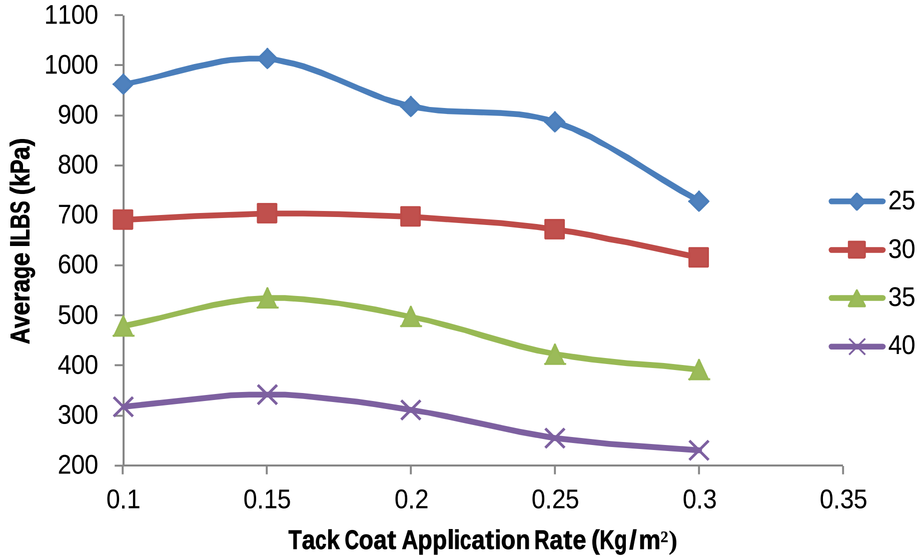


Figure 4.8 Relationship between Average ILBS and Tack Coat Application Rate at different test temperature when setting time is 6 hours.

From the figure 4.8 it is observed that in 6 hours setting time of CMS-2 type tack coat, the maximum interlayer bond strength was found with an application rate of 0.15 Kg/m^2 and it decreased when test temperature and application rate increased.

In Table 4.5 present the average interlayer bond strength when setting time is 9 hours. The highest bond strength values are observed at application rate of 0.15 Kg/m^2 at all test temperatures for the CMS-2 type of tack coat.

Table 4.5 ILBS of CMS-2 type tack coat (Considering 9 hour setting time)

Type of Tack Coat	**Application rate (Kg/m^2)**	**Average ILBS at different test temperature (kPa)**			
		25^{0}C	**30^{0}C**	**35^{0}C**	**40^{0}C**
CMS-2	0.1	1000.76	949.83	635.35	423.14
	0.15	1045.75	968.93	659.96	441.81
	0.2	975.30	874.29	578.47	386.64
	0.25	924.37	811.05	516.93	330.62
	0.3	812.32	767.34	498.26	317.88

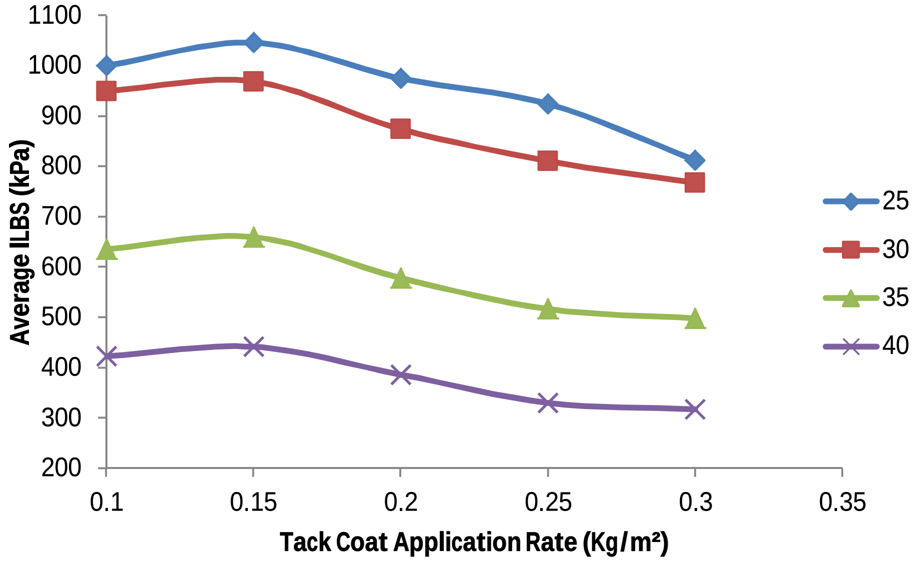


Figure 4.9 Relationship between Average ILBS and Tack Coat Application Rate at different test temperature when setting time is 9 hours.

From the figure 4.9 it is observed that in 9 hours setting time of CMS-2 type tack coat, the maximum interlayer bond strength was found with an application rate of 0.15 Kg/m^2 and it decreased when test temperature and application rate increased.

In Table 4.6 present the average interlayer bond strength when setting time is 6 hours. The highest bond strength value is observed at application rate of 0.15 Kg/m^2 at all test temperatures for the CMS-2 type of tack coat.

Table 4.6 ILBS of CMS-2 type tack coat (Considering 12 hour setting time)

Type of Tack Coat	**Application rate (Kg/m^2)**	**Average ILBS at different test temperature (kPa)**			
		25^{0}C	**30^{0}C**	**35^{0}C**	**40^{0}C**
CMS-2	0.1	760.68	566.15	348.69	293.27
	0.15	798.57	584.84	373.7	318.01
	0.2	754.60	534.21	356.73	293.34
	0.25	729.14	496.60	332.03	224.40
	0.3	628.56	474.01	274.18	212.00

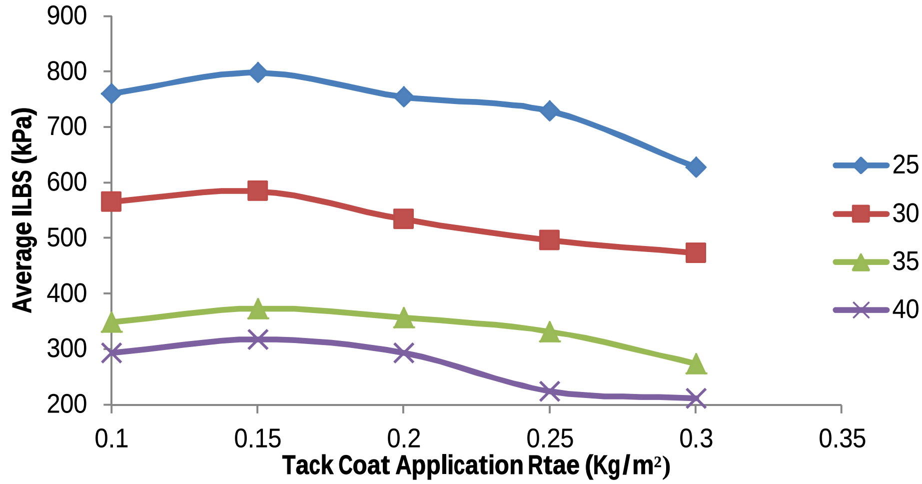


Figure 4.10 Relationship between Average ILBS and Tack Coat Application Rates at different test temperature when setting time is 12 hours.

From the figure 4.10 it is observed that in 12 hours setting time of CMS-2 type tack coat, the maximum interlayer bond strength was found with an application rate of 0.15 Kg/m^2 and it decreased when test temperature and application rate increased.

4.2.1.4 Comparisons of Average ILBS and Tack Coat Application Rates at different test temperatures with various setting times of CMS-2 type tack coat.

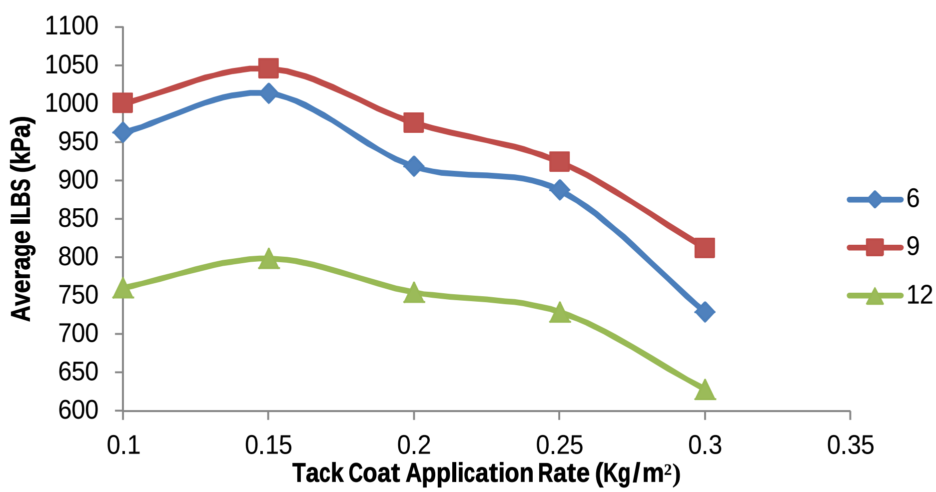


Figure 4.11 Relationship between Average ILBS and Tack Coat Application Rates at 25^{0}C for the CMS-2 type of tack coat.

Figure 4.11 shows the variation in the mean interlayer bond strength with application rates and variation in setting times obtained for CMS-2 type tack coat applied over a clean DBM surface. The highest bond strength was observed in setting time of 9 hours as compared to others at test temperature 25^{0}C with an application rate of 0.15 Kg/m^2.

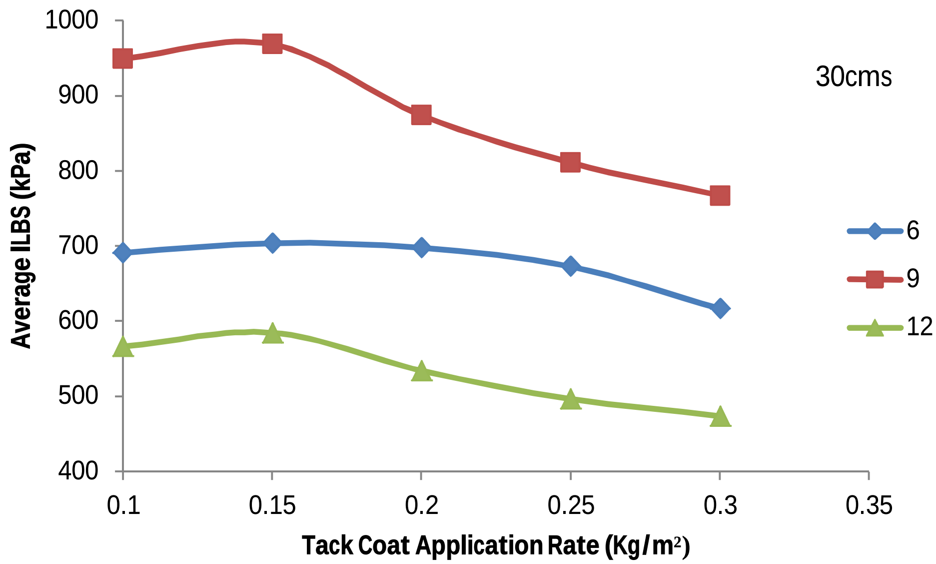


Figure 4.12 Relationship between Average ILBS and Tack Coat Application Rates at 30^{0}C for the CMS-2 type of tack coat

Figure 4.12 shows the variation in the mean interlayer bond strength with application rates and variation in setting times obtained for CMS-2 type tack coat applied over a clean DBM surface. The highest bond strength was observed in setting time of 9 hours as compared to others at test temperature 30^{0}C with an application rate of 0.15 Kg/m^2.

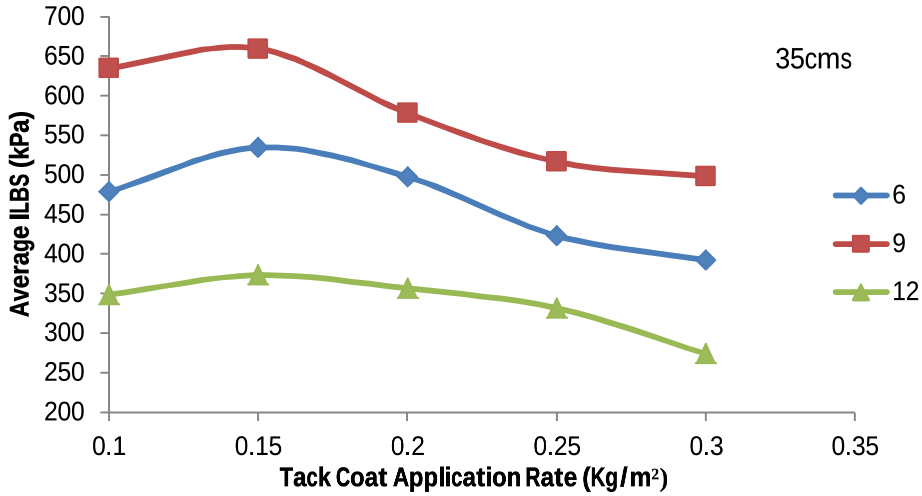


Figure 4.13 Relationship between Average ILBS and Tack Coat Application Rates at 35^{0}C for the CMS-2 type of tack coat.

Figure 4.13 shows the variation in the mean interlayer bond strength with application rates and variation in setting times obtained for CMS-2 type tack coat applied over a clean DBM surface. The highest bond strength was observed in setting time of 9 hours as compared to others at test temperature 35^{0}C with an application rate of 0.15 Kg/m^2.

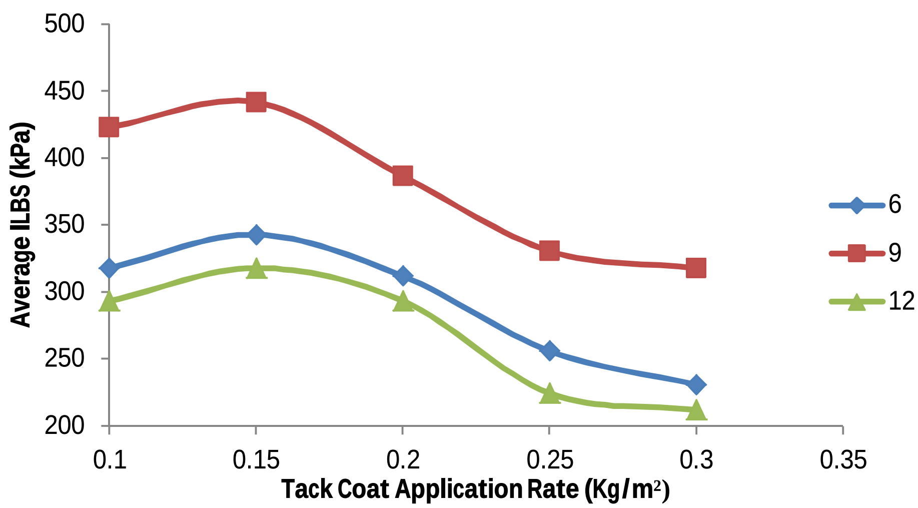


Figure 4.14 Relationship between Average ILBS and Tack Coat Application Rates at 40^{0}C for the CMS-2 type of tack coat.

Figure 4.14 shows the variation in the mean interlayer bond strength with application rates and variation in setting times obtained for CMS-2 type tack coat applied over a clean DBM surface. The highest bond strength was observed in setting time of 9 hours as compared to others at test temperature 40^0C with an application rate of 0.15 Kg/m^2.

From the above figures 4.11 to 4.14 it is observed that in all test temperatures the maximum bond strength was found out at 0.15 Kg/m^2 application rate when setting time for medium setting emulsions (CMS-2) considered as 9 hours as compared to 6 and 12 hours. The highest bond strength was obtained at 25^0C and the strength was decreased when the test temperature increases.

4.2.1.5 Variation of ILBS with rate of application when VG 30 bitumen focused as a tack coat considering various setting times.

In Table 4.7 present the interlayer bond strength when the upper layer has been compacted immediately after application of binding material (VG 30). The highest interlayer bond strength values are observed at application rate of 0.2 Kg/m^2 at all test temperatures for bitumen as a tack coat.

Table 4.7 ILBS of VG 30 as a tack coat (Considering 0 hour setting time)

Type of Tack Coat	Application rate (Kg/m^2)	Average ILBS at different test temperature (kPa)			
		25^0C	30^0C	35^0C	40^0C
VG 30	0.1	672.27	600.12	392.58	355.66
	0.2	723.20	653.17	497.84	428.56
	0.3	628.13	491.47	355.66	280.96

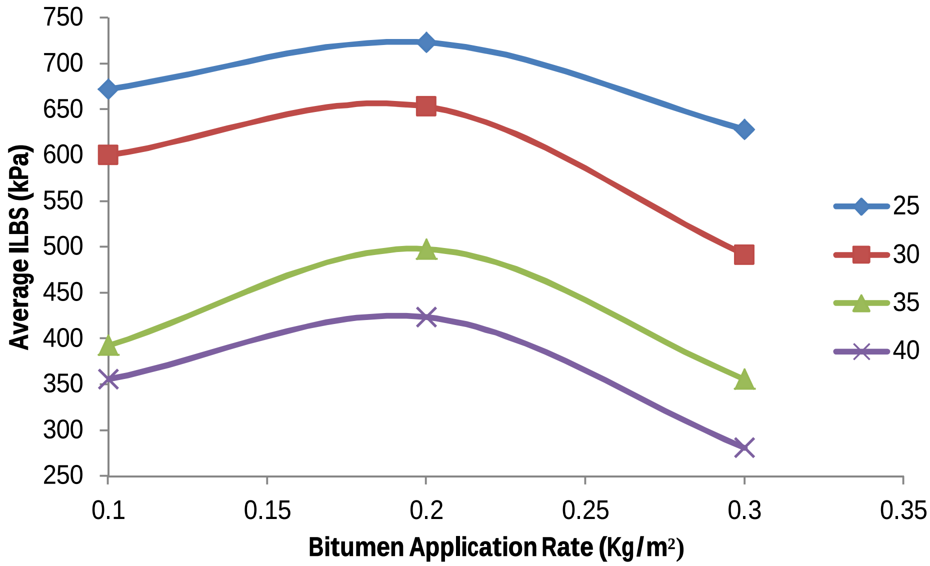


Figure 4.15 Relationship between Average ILBS and Application Rates of bitumen at different test temperature considering 0 hour setting time.

From figure 4.15 it is observed that when bitumen is focused as a tack coat, the maximum interlayer bond shear strength was found at 0.2 Kg/m^2 rate of application at all test temperatures when the upper layer has been compacted immediately after application of bitumen and the strength decreased when test temperature and application rate increased.

In Table 4.8 present the interlayer bond strength when setting time is 0.5 hours. The highest bond strength values are observed at application rate of 0.2 Kg/m^2 at all test temperatures for bitumen as a tack coat.

Table 4.8 ILBS of VG 30 as a tack coat (Considering 0.5 hour setting time)

Type of Tack Coat	**Application rate (Kg/m^2)**	**Average ILBS at different test temperature (kPa)**			
		25^{0}C	**30^{0}C**	**35^{0}C**	**40^{0}C**
VG 30	0.1	773.28	672.27	642.14	435.45
	0.2	868.35	798.74	691.37	572.11
	0.3	811.05	640.86	560.65	367.97

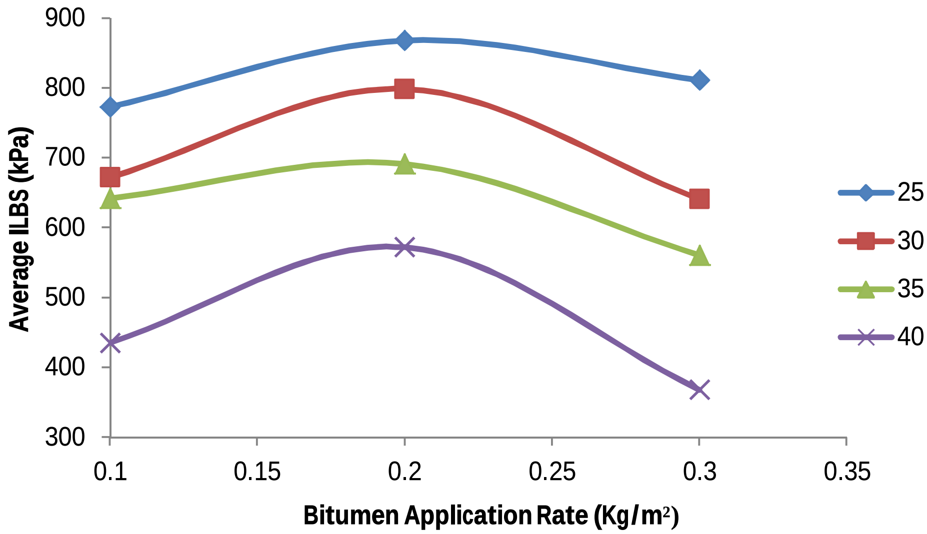


Figure 4.16 Relationship between Average ILBS and Application Rates of bitumen at different test temperature considering 0.5 hour setting time.

From figure 4.16 it is observed that when bitumen is focused as a tack coat, the maximum interlayer bond shear strength was found at 0.2 Kg/m^2 rate of application at all test temperatures when the upper layer has been compacted 0.5 hours after application of bitumen and the strength decreased when test temperature and application rate increased.

In Table 4.9 present the interlayer bond strength when setting time is 1 hour. The highest bond strength value is observed at application rate of 0.2 Kg/m^2 at all test temperatures for bitumen as a tack coat.

Table 4.9 ILBS of VG 30 as a tack coat (Considering 1 hour setting time)

Type of Tack Coat	**Application rate (Kg/m^2)**	**Average ILBS at different test temperature (kPa)**			
		25^{0}C	**30^{0}C**	**35^{0}C**	**40^{0}C**
VG 30	0.1	760.97	653.17	522.45	392.16
	0.2	836.94	723.20	628.55	491.47
	0.3	735.51	610.30	491.47	324.25

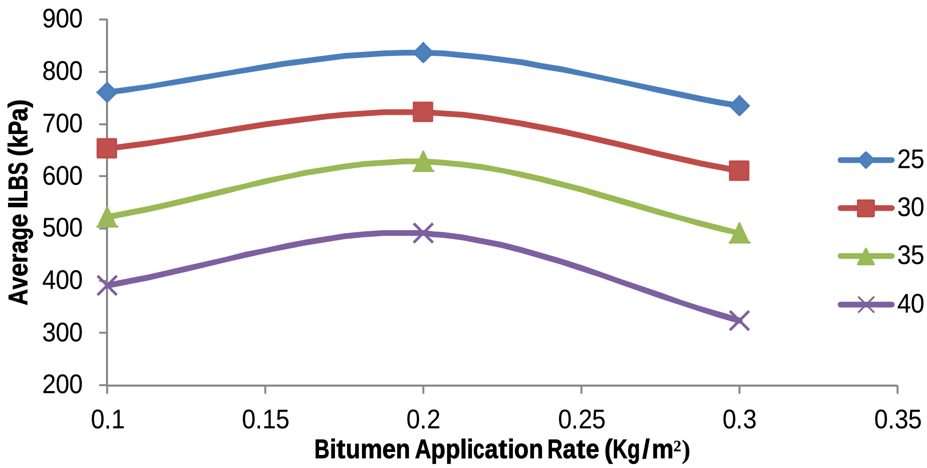


Figure 4.17 Relationship between Average ILBS and Application Rates of bitumen at different test temperature considering 1 hour setting time.

From figure 4.17 it is observed that when bitumen is focused as a tack coat, the maximum interlayer bond shear strength was found at 0.2 Kg/m^2 rate of application at all test temperatures when the upper layer has been compacted 1 hour after application of bitumen and the strength decreased when test temperature and application rate increased.

4.2.1.6 Comparisons of Average ILBS and Application Rates at different test temperatures with various setting times of VG 30 bitumen as a tack coat.

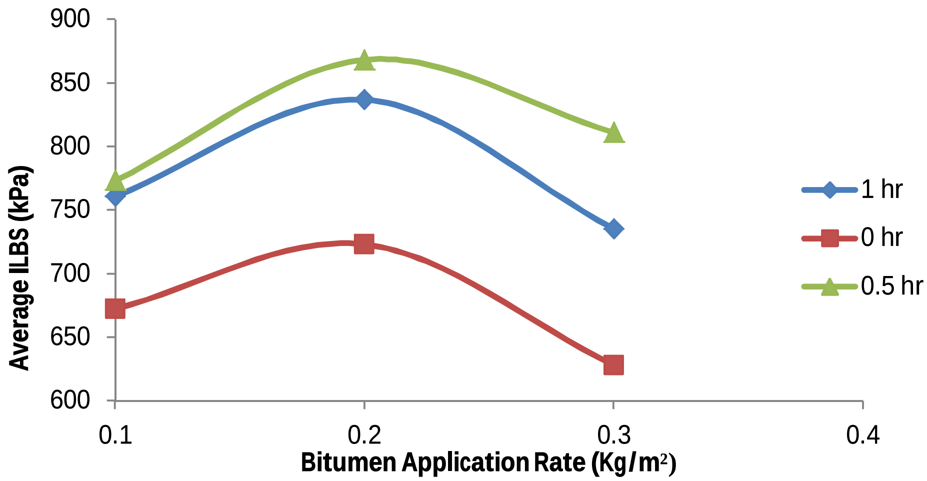


Figure 4.18 Relationship between Aerage ILBS and Application Rates of bitumen at 25^{0}C test temperature considering all setting time.

Figure 4.18 shows the variation in the mean interlayer bond strength with application rates and variation in setting times obtained for VG 30 binder as a tack coat applied over a clean DBM surface. The highest bond strength was observed in setting time of 0.5 hours at test temperature 25^0C with an application rate of 0.2 Kg/m^2.

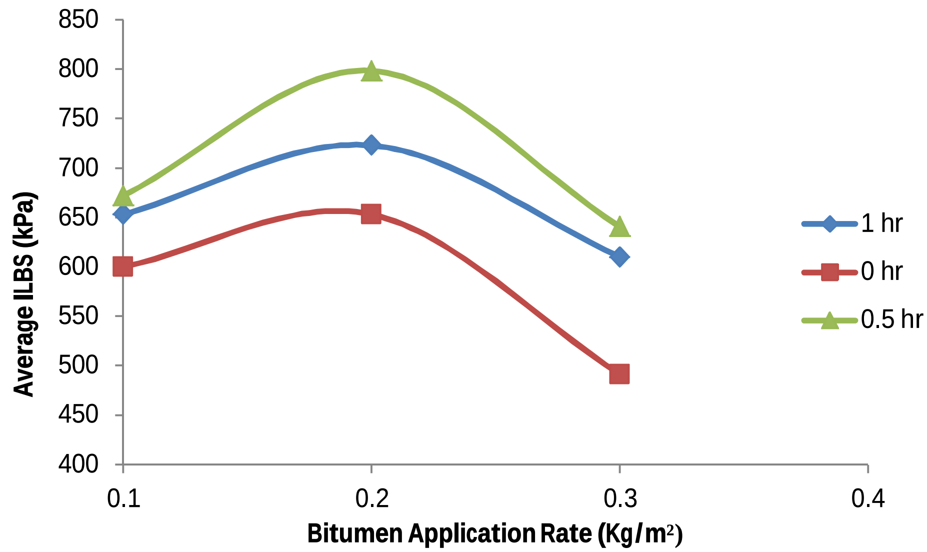


Figure 4.19 Relationship between Average ILBS and Application Rates of bitumen at 30^0C test temperature considering all setting time.

Figure 4.19 shows the variation in the mean interlayer bond strength with application rates and variation in setting times obtained for VG 30 binder as a tack coat applied over a clean DBM surface. The highest bond strength was observed in setting time of 0.5 hours at test temperature 30^0C with an application rate of 0.2 Kg/m^2.

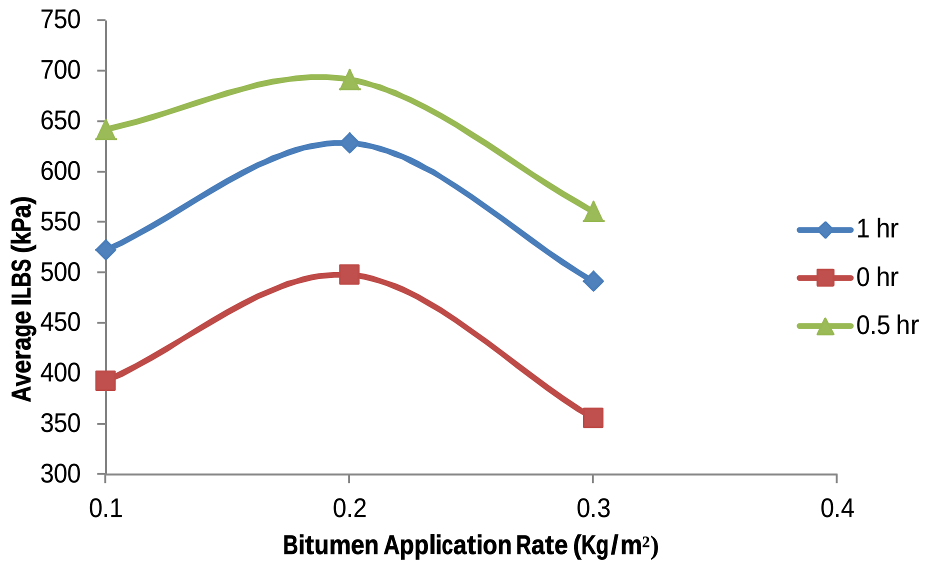


Figure 4.20 Relationship between Average ILBS and Application Rates of bitumen at 35^{0}C test temperature considering all setting time.

Figure 4.20 shows the variation in the mean interlayer bond strength with application rates and variation in setting times obtained for VG 30 binder as a tack coat applied over a clean DBM surface. The highest bond strength was observed in setting time of 0.5 hours at test temperature 35^{0}C with an application rate of 0.2 Kg/m^2.

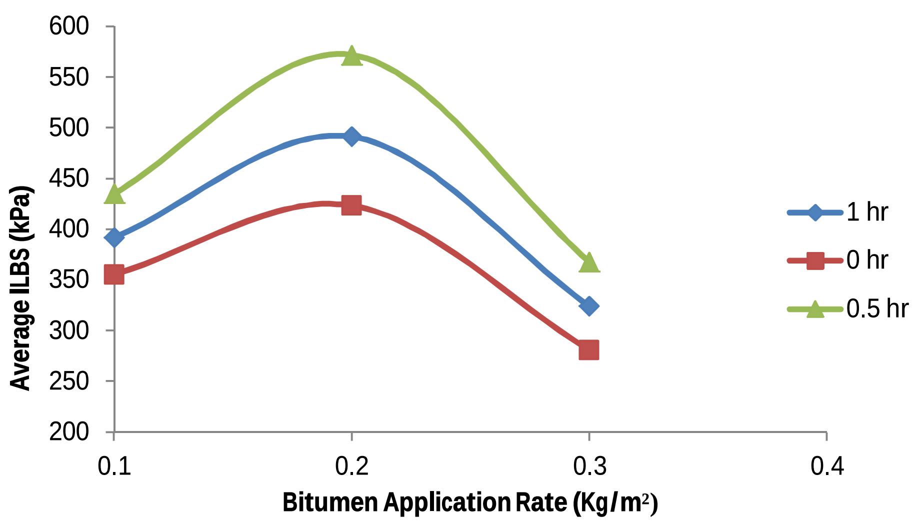


Figure 4.21 Relationship between Average ILBS and Application Rates of bitumen at 40^{0}C test temperature considering all setting time.

Figure 4.21 shows the variation in the mean interlayer bond strength with application rates and variation in setting times obtained for VG 30 binder as a tack coat applied over a clean DBM surface. The highest bond strength was observed in setting time of 0.5 hours at test temperature 40^0C with an application rate of 0.2 Kg/m^2.

From above figures 4.18 to 4.21, when bitumen focused as a bonding material the average maximum interlayer bond strength was observed at 25^0C compared to other three test temperatures with an application rate 0.2 Kg/m^2 at 0.5 hours setting time for it. The bond strength was decreased when the test temperatures and the application rate increased.

4.2.1.7 Variation of ILBS considering various time interval between successive laying between DBM and BC bituminous paving layers.

In Table 4.10 present interlayer bond strength when there is no tack coat used for creating bonds between DBM and BC layer with varying the time interval between successive laying between them.

Table 4.10 ILBS without using any tack coat

Type of Tack Coat	**Time interval between Successive laying (Hour)**	**Average ILBS at different test temperature (kPa)**			
		25^0C	**30^0C**	**35^0C**	**40^0C**
No Tack Coat	0	1038.9	994.40	729.56	578.47
	1	836.52	760.97	616.67	466.85
	2	760.97	628.98	553.86	417.20
	3	689.25	572.53	504.63	398.95
	6	572.53	435.87	348.87	305.58

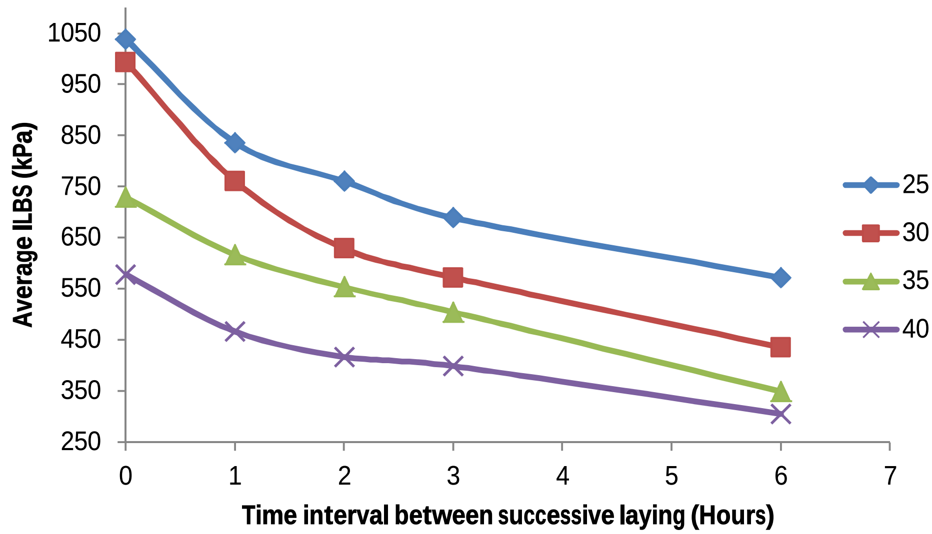


Figure 4.22 Relationship between Average ILBS and Time interval between successive laying of overlay at different test temperature with no tack coat used.

From the figure 4.22 it is observed that the maximum interlayer bond strength was found out at different test temperatures when the overlay placed over the freshly compacted DBM layer and the strength decreased when test temperature and duration of compaction increased.

4.2.2 Interlayer Bond Strength for Bituminous Macadam (BM) and Semi Dense Bituminous Concrete (SDBC) Combination.

4.2.2.1 Variation of ILBS with rate of application for a CRS-1 type tack coat considering a 1 hour setting time.

In Table 4.11 present the interlayer bond strength when setting time is 1 hour. The highest interlayer bond strength value is observed at application rate of 0.15 Kg/m^2 at all test temperatures for CRS-I type tack coat for BM/SDBC combination.

Table 5.11 ILBS of CRS-1 type tack coat

Type of Tack Coat	Application rate (Kg/m^2)	Average ILBS at different test temperature (kPa)			
		25^{0}C	30^{0}C	35^{0}C	40^{0}C
CRS-1	0.1	773.28	665.90	523.30	367.97
	0.15	930.74	786.01	597.15	448.18
	0.2	862.41	635.35	492.32	348.87
	0.25	754.60	566.17	423.56	293.27
	0.3	665.90	460.91	386.64	255.50

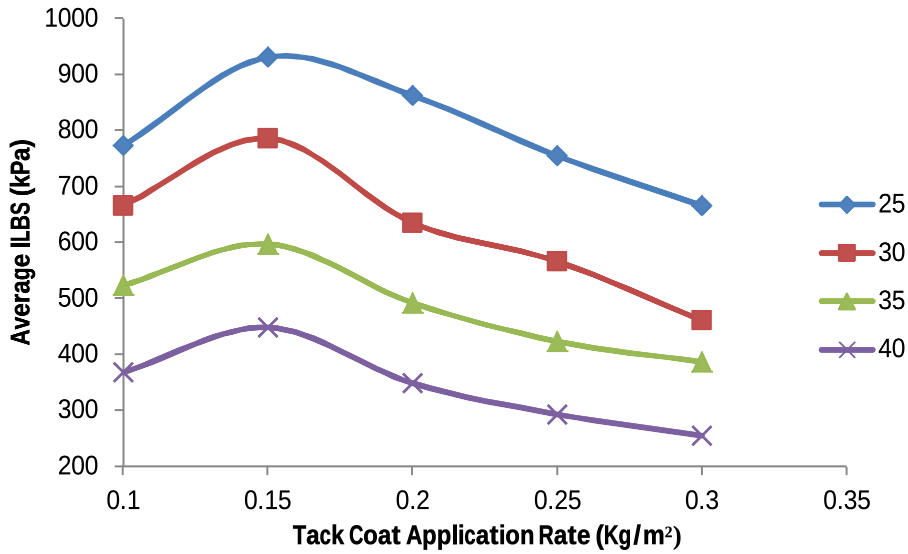


Figure 4.23 Relationship between Average ILBS and Tack Coat Application Rates at different test temperature for the CRS-1 type of tack coat.

From the figure 4.23 it is observed that in the CRS-1 type of tack coat, the maximum interlayer bond strength was found at all test temperatures with an application rate of 0.15 Kg/m^2 and the strength was decreased when test temperature and application rate increased.

4.2.2.2 Variation of ILBS with rate of application for a CMS-2 type tack coat considering 9 hours setting times.

In Table 4.12 present the interlayer bond strength when setting time is 9 hours. The highest interlayer bond strength values are observed at application rate of 0.15 Kg/m^2 at all test temperatures for a CMS-2 type tack coat for BM/SDBC combination.

Table 4.12 ILBS of CMS-2 type tack coat

Type of Tack Coat	Application rate (Kg/m^2)	Average ILBS at different test temperature (kPa)			
		25^{0}C	30^{0}C	35^{0}C	40^{0}C
CMS-2	0.1	760.97	578.47	491.47	305.58
	0.15	918.00	748.24	587.81	411.26
	0.2	855.19	597.15	448.60	274.59
	0.25	760.55	553.86	404.89	243.19
	0.3	654.02	448.18	361.60	211.78

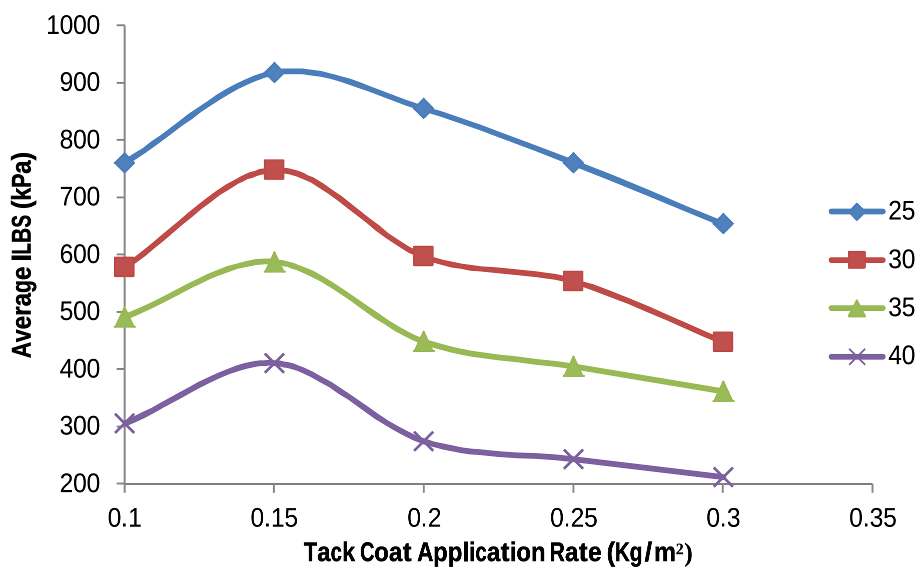


Figure 4.24 Relationship between Average ILBS and Tack Coat Application Rates at different test temperature for the CMS-2 type of tack coat.

From the figure 4.24 it is observed that in the CMS-2 type of tack coat, the maximum interlayer bond strength found at all test temperatures with application rate 0.15 Kg/m^2 and the strength was decreased when test temperature and application rate increased.

4.2.2.3 Comparisons of Average ILBS and Tack Coat Application Rates of CMS-2 and CRS-1 type tack coat at different test temperatures.

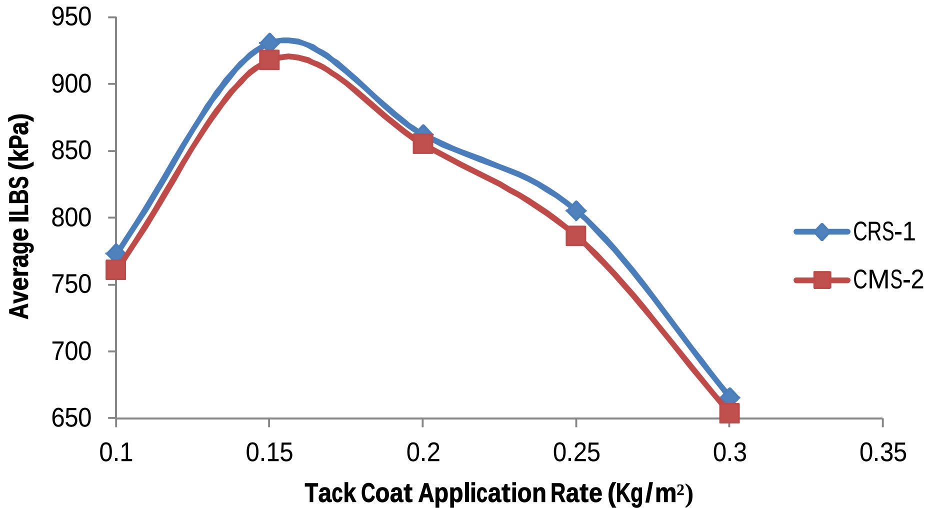


Figure 4.25 Relationships between Average ILBS and Application Rates at 25^{0}C

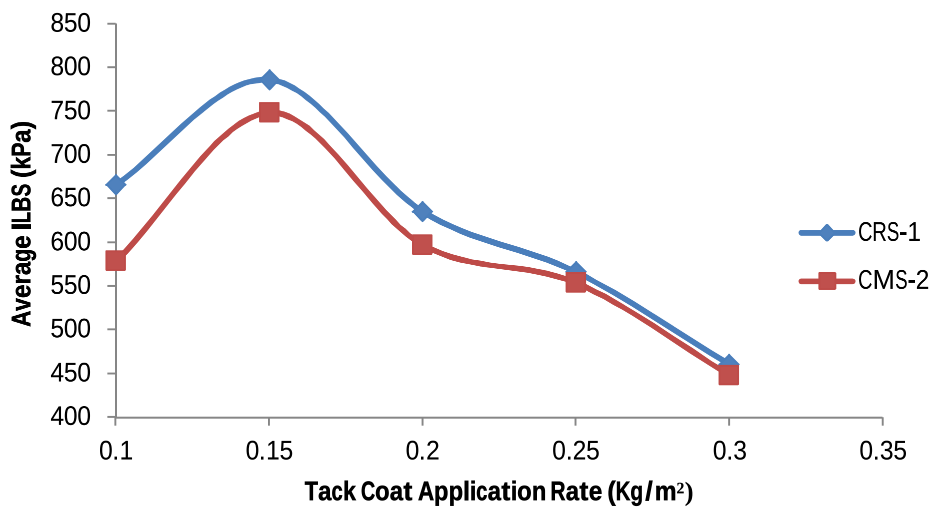


Figure 4.26 Relationships between Average ILBS and Application Rates at 30^{0}C

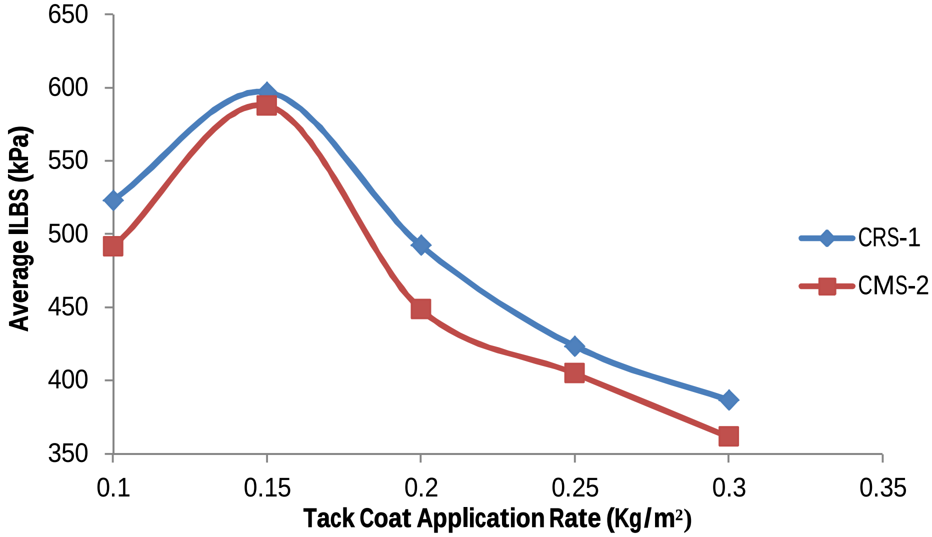


Figure 4.27 Relationships between Average ILBS and Application Rates at 35^{0}C

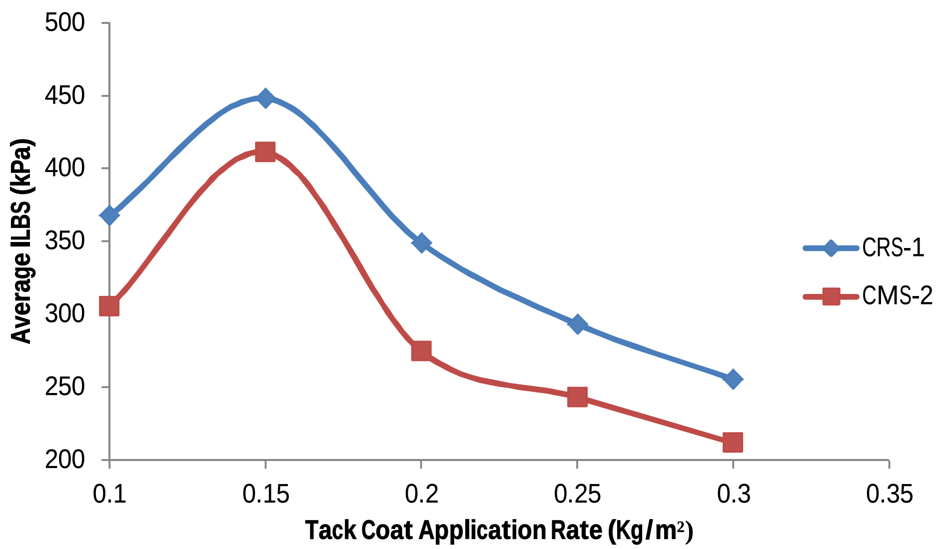


Figure 4.28 Relationships between Average ILBS and Application Rates at 40^{0}C

From figures 4.25 to 4.28 observed that the CRS-1 type of tack coat has been given more bond strength as compared to CMS-2 type at an application rate of 0.15 Kg/m^2.It was also found that when the test temperatures and rate of application increased, the interlayer bond strength decreased.

4.3 Overall Performance of Inter Layer Bond Strength

4.3.1 ILBS comparisons between two types of tack coat, bitumen as tack coat and with no tack coat at different test temperature for the Interface of DBM and BC type of combination.

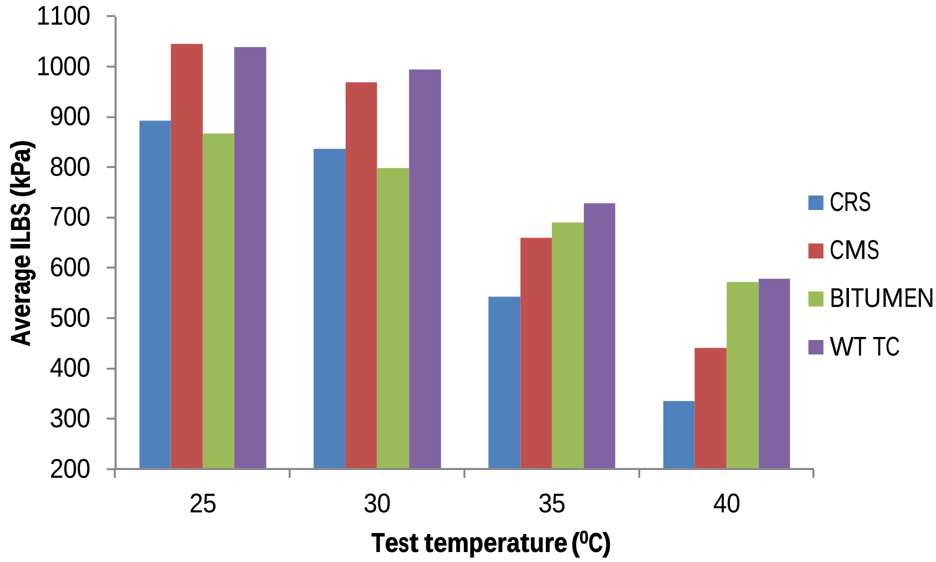


Figure 4.29 Comparisons of ILBS at different test temperature made

From the figure 4.29, the maximum bond strength was found at 25^0C among all others three cases considered as bonding materials for DBM and BC type of combination of the bituminous paving layer. When the bituminous concrete (BC) considered as upper layer placed immediately over the freshly compacted dense bitumen macadam (DBM) layer was given maximum interlayer bond strength as compared to all others. The interlayer strength decreased when the test temperatures, rate of applications and time interval between successive laying increased.

4.3.2 ILBS comparisons between two types of tack coat at different test temperature for Interface of BM and SDBC type of combination.

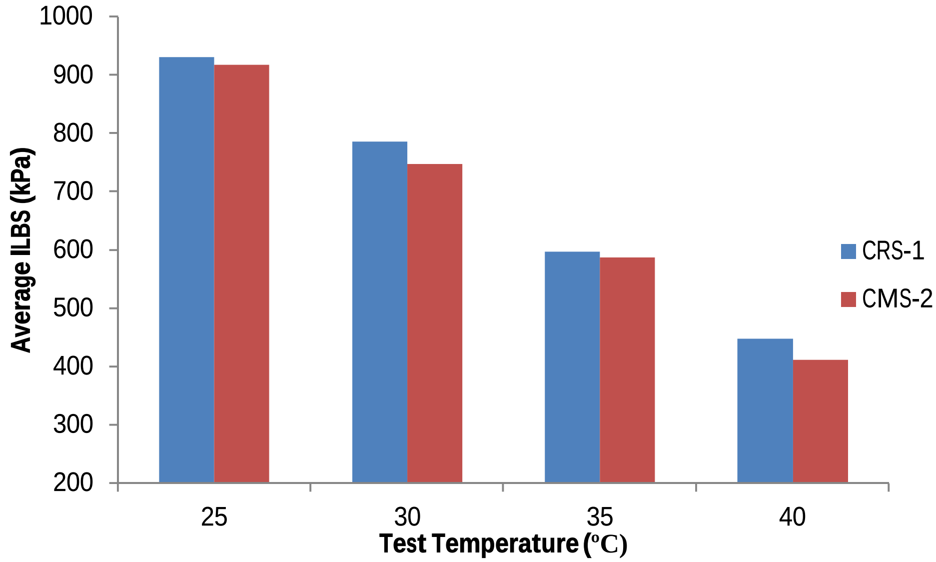


Figure 4.30 Comparisons of ILBS at different test temperature made

From the figure 4.30, the maximum mean interlayer bond strength was found at 25^0C among all other three test temperatures considered for the BM and SDBC type of combination for the bituminous paving layer. In all cases the CRS-1 type emulsion results more as compared to CMS-2 type of tack coat. The interlayer strength decreased when the test temperatures, rate of applications and durations of compaction increased

Chapter V

Conclusions and Future Scope

5.1 Introduction

In this chapter the conclusions of the laboratory study carried out for evaluating the interlayer bond strength between two types of bituminous paving layer have been summarized. The scopes and recommendation for the future research work are also discussed in this chapter.

5.2 Conclusions

A study has been made in this project to evaluate the interlayer bond strength in the laboratory for different types of tack coat using laboratory prepared samples for DBM/BC and BM/SDBC layer combinations. A special device has been designed and fabricated, which can be fitted to the loading frame of the Modified Marshall Test apparatus to determine the interlayer bond strength of two-layered bituminous specimens. The specimens have been tested at four different test temperatures, namely 25^0, 30^0, 35^0 and 40^0C, which are very common in our country. A specimen basically consists of two bituminous layers, bonded together by emulsion or bitumen. The upper and lower layer combination is either DBM or BC or BM and SDBC respectively. Various application rates have been tried and in case of emulsion, different setting times have been tried. All such variations in materials and sample casting methods have been attempted to explore the optimum condition for appropriate bond strength in a particular situation. The following conclusions are drawn from the results of the tests conducted.

DBM/BC Combination

- It is observed that for CRS-1, maximum interlayer bond strength results at 0.25 Kg/m^2 application rate in all test temperature conditions used and for CMS-2, at 0.15 Kg/m^2 application rate irrespective of different test temperatures. These optimum application rates are also found for all setting times considered for both types of emulsions.

- In the cationic medium setting type of emulsion used as tack coat, the maximum interlayer bond strength was found when setting time was at 9 hours and in the cationic rapid setting type of emulsion, maximum interlayer strength was observed when setting was at 1 an hour.
- When conventional VG 30 bitumen is used as a tack coat, the maximum interlayer bond strength is observed at 0.2 Kg/m^2 application rate when setting time was at 0.5 hours in all test temperatures used.
- When no tack coat is used, maximum bond strength at the interface available when the upper layer mix is laid and compacted immediately after the lower layer compaction was completed. If the duration of compaction increased between two layers, the interlayer bond strength decreased.
- At a test temperature 25^{0}C, all types of tack coat used and other considerations taken for observing the interlayer bond strength have been found maximum value as compared to other test temperatures.

BM/SDBC Combination

- It is determined that for CRS-1, maximum interlayer bond strength results at a 0.15 Kg/m^2 application rate in all test temperature conditions used and for CMS-2, at the 0.15 Kg/m^2 application rate irrespective of different test temperatures.
- The interlayer bond strength is decreased when the test temperature increased for both types of tack coat used. The maximum bond strength has been found out at 25^{0}C for both types of tack coat used.

5.3 Future Scope of Works

- Analysis the bond strength using finite element method and comparison of laboratory results with theoretical work.
- Experimentation using the fabricated device in respect of various loading combinations.
- Comparison of the experimental results with that given in the literature and experiments conducted earlier.
- Testing of field core samples and comparison with laboratory prepared ones.

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